PHILOSOPHICAL TRANSACTIONS.

I. THE BAKERIAN LECTURE.—*On the nature of the Force by which Bodies are repelled from the Poles of a Magnet; to which is prefixed, an Account of some Experiments on Molecular Influences.* By JOHN TYNDALL, *Ph.D., F.R.S., Membre de la Société Hollandaise des Sciences; Foreign Member of the Physical Society of Berlin, and Professor of Natural Philosophy in the Royal Institution.*

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INTRODUCTION.

FROM the published account of his researches it is to be inferred, that the same heavy glass, by means of which he produced the rotation of the plane of polarization of a luminous ray, also led Mr. FARADAY to the discovery of the diamagnetic force. A square prism of the glass, 2 inches long and 0·5 of an inch thick, was suspended with its length horizontal between the two poles of a powerful electro-magnet: on developing the magnetism the prism moved round its axis of suspension, and finally set its length at right angles to a straight line drawn from the centre of one pole to that of the other. A prism of ordinary magnetic matter, similarly suspended, would, as is well known, set its longest dimension from pole to pole. To distinguish the two positions here referred to, Mr. FARADAY introduced two new terms, which have since come into general use: he called the direction parallel to the line joining the poles, the *axial* direction, and that perpendicular to the said line, the *equatorial* direction.

The difference between this new action, and the ordinary magnetic action, was further manifested, when a fragment of the heavy glass was suspended before a single magnetic pole: the fragment was repelled when the magnetism was excited; and to the force which produced this repulsion Mr. FARADAY gave the name of *diamagnetism*.

Numerous other substances were soon added to the heavy glass, and, among the metals, it was found that bismuth possessed the new property in a comparatively exalted degree. A fragment of this substance was forcibly repelled by either of the poles of a magnet; while a thin bar of the substance, or a glass tube containing the bismuth in fragments, or in powder, suspended between the two poles of a horseshoe magnet, behaved exactly like the heavy glass, and set its longest dimension equatorial.

These exhaustive researches, which rendered manifest to the scientific world the existence of a pervading natural force, glimpses of which merely had been previously obtained by BRUGMANN and others, were made public in 1846; and in the following year M. PLÜCKER made known his beautiful discovery of the action of a magnet upon crystallized bodies. His first result was, that when any crystal whatever was suspended between the poles of a magnet, with its optic axis horizontal, a repulsive force was exerted on the said axis, in consequence of which it receded from the poles and finally set itself at right angles to the line joining them. Subsequent experiments, however, led to the conclusion, that the axes of optically negative crystals only experienced this repulsion, while the axes of positive crystals were attracted; or, in other words, set themselves from pole to pole.

The attraction and repulsion, here referred to, were ascribed by M. PLÜCKER to the action of a new force, entirely independent of the magnetism or diamagnetism of the mass of the crystal *. Shortly after the publication of M. PLÜCKER's first memoir, Mr. FARADAY observed the remarkable magnetic properties of crystallized bismuth; and his researches upon this, and one or two kindred points, formed the subject of the Bakerian Lecture before the Royal Society for the year 1849.

* "*The force which produces this repulsion is independent of the magnetic or diamagnetic condition of the mass of the crystal; it diminishes less, as the distance from the poles of the magnet increases, than the magnetic and diamagnetic forces emanating from these poles and acting upon the crystal.*"—Prof. PLÜCKER in POGGENDORFF's Annalen, vol. lvii. No. 10; TAYLOR's Scientific Memoirs, vol. v. p. 353.

The forces emanating from the poles of a magnet are thus summed up by M. PLÜCKER:—

1st. The magnetic force in a strict sense.

2nd. The diamagnetic action discovered by FARADAY.

3rd. The action exerted on the optic axis of crystals (and that producing the rotation of the plane of polarization which probably corresponds to it). *The second diminishes more with the distance than the first, and the first more than the third.*—TAYLOR's Scientific Memoirs, vol. v. p. 380.

The crystal (cyanite) does not point according to the magnetism of its substance, *but only in obedience to the magnetic action upon its optic axes.*—Letter to Mr. FARADAY, Phil. Mag. vol. xxxiv. p. 451. The italics in all cases are M. PLÜCKER's own.

M. DE LA RIVE states the view of M. PLÜCKER to be:—"that the axis in its quality as axis, and independently of the very nature of the substance of the crystal, enjoys peculiar properties, more frequently in opposition to those possessed by the substance itself, or which at least are altogether independent of it."—Treatise on Electricity, vol. i. p. 359.

Through the admirable lectures of Professor Bunsen on Electro-chemistry in 1848, I was first made acquainted with the existence of the diamagnetic force; and in the month of November 1849 my friend Professor Knoblauch, then of Marburg, now of the University of Halle, suggested to me the idea of repeating the experiments of M. Plücker and Mr. Faraday. He had procured the necessary apparatus with the view of prosecuting the subject himself, but the pressure of other duties prevented him from carrying out his intention. I adopted the suggestion and entered upon the inquiry in M. Knoblauch's cabinet. Our frequent conversations upon the subject led to the idea of our making a joint publication of the results: this we accordingly did, in two papers, the first of which, containing a brief account of some of the earliest experiments, appeared in the Philosophical Magazine for March 1850, and some time afterwards in Poggendorff's Annalen; while the second and principal memoir appeared in the Philosophical Magazine for July 1850, and in Poggendorff's Annalen about January 1851*. I afterwards continued my researches in the private laboratory of Professor Magnus of Berlin, who with prompt kindness and a lively interest in the furtherance of the inquiry, placed all necessary apparatus at my disposal. The results of this investigation are described in a paper published in the Philosophical Magazine for September 1851, and in Poggendorff's Annalen, vol. lxxxiii.

In these memoirs it was shown that the law according to which the axes of positive crystals are attracted and those of negative crystals repelled, was contradicted by the deportment of numerous crystals both positive and negative. It was also proved that the force which determined the position of the optic axes in the magnetic field was not independent of the magnetism or diamagnetism of the mass of the crystal; inasmuch as two crystals, of the same form and structure, exhibited altogether different effects, when one of them was magnetic and the other diamagnetic. It was shown, for example, that pure carbonate of lime was diamagnetic, and always set its optic axis equatorial; but that when a portion of the calcium was replaced by an isomorphous magnetic constituent, which neither altered the structure nor affected the perfect transparency of the crystal, the optic axis set itself from pole to pole. The various complex phenomena exhibited by crystals in the magnetic field were finally referred to the modification of the magnetic and diamagnetic forces by the peculiarities of molecular arrangement.

This result is in perfect conformity with all that we know experimentally regarding the connexion of matter and force. Indeed it may be safely asserted that every force which makes matter its vehicle of transmission must be influenced by the manner in which the material particles are grouped together. The phenomena of double refraction and polarization illustrate the influence of molecular aggregation upon light. Wertheim has shown that the velocity of sound through wood, *along* the fibre, is

* The memoirs in the Philosophical Magazine were written by me, and the second one has, I believe, been translated into German by Dr. Krönig: the papers in Poggendorff's Annalen were edited by my colleague. —J. T.

about five times its velocity *across* the fibre: De la Rive, DeCandolle and myself have shown the influence of the same molecular grouping upon the propagation of heat. In the first section of the present paper, the influence of the molecular structure of wood upon its magnetic deportment is described: De Senarmont has shown that the structure of crystals endows them with different powers of calorific conduction in different directions: Knoblauch has proved the same to be true, with regard to the transmission of radiant heat: Wiedeman finds the passage of frictional electricity along crystals to be affected by structure; and some experiments, which I have not yet had time to follow out, seem to prove, that bismuth may, by the approximation of its particles, be caused to exhibit, in a greatly increased degree, those singular effects of induction which are so strikingly exhibited by copper, and other metals of high conducting power.

Indeed the mere *à priori* consideration of the subject must render all the effects here referred to extremely probable. Supposing the propagation of the forces to depend upon a subtle agent, distinct from matter, it is evident that the progress of such an agent from particle to particle must be influenced by the manner in which these particles are arranged. If the particles be twice as near each other in one direction as in another, it is certain that the agent of which we speak will not pass with the same facility in both directions. Or supposing the effects to which we have alluded to be produced by motion of some kind, it is just as certain that the propagation of this motion must be affected by the manner in which the particles which transmit it are grouped together. Whether, therefore, we take the old hypothesis of imponderables, or the new, and more philosophic one, of modes of motion, the result is still the same.

If this reasoning be correct, it would follow, that, if the molecular arrangement of a body be changed, such a change will manifest itself by an alteration of deportment towards any force operating upon the body: the action of compressed glass upon light, which Wertheim in his recent researches* has so beautifully turned to account in the estimation of pressures, is an illustration in point; and the inference also receives the fullest corroboration from experiments, some of which are recorded in the papers alluded to, and which show that all the phenomena of magnecrystallic action may be produced by simple mechanical agency. What the crystalline forces do in one case, mechanical force, under the control of the human will, accomplishes in the other. A crystal of carbonate of iron, for example, suspended in the magnetic field, exhibits a certain deportment: the crystal may be removed, pounded into the finest dust, and the particles so put together that the mass shall exhibit the same deportment as before. A bismuth crystal suspended in the magnetic field, with its planes of principal cleavage vertical, will set those planes equatorial; but if the crystalline planes be squeezed sufficiently together by a suitable mechanical force, this deportment is quite changed, and the line which formerly set equatorial now sets axial†.

* Phil. Mag. October and November 1854.

† Phil. Mag. vol. ii. Ser. 4. p. 183.

Thus we find that the influence of crystallization may be perfectly imitated, and even overcome, by simple mechanical agencies. It would of course be perfectly unintelligible were we to speak of any direct action of the magnetic force upon the force by which the powdered carbonate of iron, or the solid cube of bismuth, is compressed; such an idea, however, appears scarcely less tenable than another which seems to be entertained by some who feel an interest in this subject; namely, that there is a direct action of the magnet upon the molecular forces which built the crystal. The function of such forces, as regards the production of the effects, is, I believe, *mediate*; the molecular forces are exerted in placing the particles in position, and the subsequent phenomena, whether exhibited in magnecrystallic action, in the bifurcation and polarization of a luminous ray, or in the modification of any other force transmitted through the crystal, are not due to the action of force upon force, except through the intermediation of the particles referred to*.

The foregoing introductory statement will, perhaps, sufficiently indicate the present aspect of this question. The object I proposed to myself in commencing the inquiry now laid before the Royal Society, is to obtain, if possible, clearer notions of the nature of the diamagnetic force than those now prevalent; for though, in the preceding paragraphs, we have touched upon some of the most complex phenomena of magnetism and diamagnetism, and are able to produce these phenomena at will, the greatest diversity of opinion still prevails as to the real relationship of the two forces. The magnetic force, we know, embraces both attraction and repulsion, thus exhibiting that wonderful dual action which we are accustomed to denote by the term polarity. Mr. FARADAY was the first who proposed the hypothesis that diamagnetic bodies, operated on by magnetic forces, possess a polarity "the same in kind as, but the reverse in direction, of that acquired by iron, nickel, and ordinary magnetic bodies under the same circumstances†." M. W. WEBER sought to confirm this hypothesis by a series of experiments, wherein the excitement of the supposed diamagnetic polarity was applied to the generation of induced currents—apparently with perfect success. Mr. FARADAY afterwards showed, and his results were confirmed by M. VERDET, that effects similar to those described by the distinguished German, were to be attributed, not to the excitement of diamagnetic polarity, but to the generation of ordinary induced currents in the metallic mass. On the question of polarity Mr. FARADAY's results were negative, and he therefore, with philosophic caution, holds himself unpledged to his early opinion. M. WEBER, however, still retains his belief in the reverse polarity of diamagnetic bodies, whereas WEBER's countryman M. VON FEILITSCH, in a series of memoirs recently published in POGGENDORFF's Annalen, contends that the polarity of

* The influence of molecular aggregation probably manifests itself on a grand scale in nature. The Snowdon range of mountains, for example, is principally composed of slate rock, whose line of strike is nearly north and south. The magnetic properties of this rock I find, by some preliminary experiments, to be very different along the cleavage from what they are across it. I cannot help thinking that these vast masses, in their present position, must exert a different action on the magnetic needle from that which would be exerted if the line of strike were east and west.

† Experimental Researches, 2429, 2430.

diamagnetic bodies is precisely the same as that of magnetic ones. In this unsettled state of the question nothing remained for me but a complete examination of the nature of the diamagnetic force, and a thorough comparison of its phenomena with those of ordinary magnetism. This has been attempted in the following pages, with what success it must be left to the reader to decide.

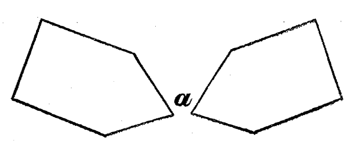
Before entering upon the principal inquiry, I will introduce one or two points which arose incidentally from the investigation, and which appear to be worth recording.

I. ON THE MAGNETIC PROPERTIES OF WOOD.

No experiments have yet been made, to determine the influence of structure upon the magnetic deportment of this substance; and even on the question whether it is magnetic, like iron, or diamagnetic, like bismuth, differences of opinion appear to prevail. Such differences are to be referred to the extreme feebleness of the force proper to the wood itself, and its consequent liability to be masked by extraneous impurity. In handling the substance intended for experiment the fingers must be kept perfectly clean, and frequent washing is absolutely necessary. After reducing the substance to a regular shape, so as to annul the influence of exterior form, its outer surface must be carefully removed by glass, and the body afterwards suspended by a very fine fibre between the poles of a strong electro-magnet.

The first step in the present inquiry was to ascertain whether the substance examined was paramagnetic* or diamagnetic. It is well known, that, in experiments of this kind, moveable masses of soft iron are placed upon the ends of the electro-magnet, the distance between the masses being varied to suit the experiment. In front of a pointed mass of iron of this kind, a cube of wood was suspended, and if, on exciting the magnet, the cube was repelled by the point, it was regarded as diamagnetic; if attracted, it was considered to be paramagnetic. The force was considerably intensified by placing the two moveable poles as in fig. 1, and suspending the cube at *a* on the same level with the points; a diamagnetic body placed there is, on the development of the magnetic force, forcibly driven *from* the line which unites the points, while a magnetic body is forcibly drawn in between them.

Fig. 1.



Having thus observed the deportment of the mass, the cube was next suspended between the *flat* ends of the poles sketched in fig. 1. The parallel faces were about three-quarters of an inch apart, and in each case the fibre of the suspended wood was horizontal. The specimen first examined was Beef-wood: suspended in the position *a*, fig. 1, the mass was repelled: suspended between the flat poles, on exciting the mag-

* The effects exhibited by iron and by bismuth come properly under the general designation of *magnetic* phenomena: to render their subdivision more distinct Mr. Faraday has recently introduced the word *paramagnetic* to denote the old magnetic effects, of which the action of iron is an example. Wherever the word *magnetic* occurs, without the prefix, it is always the old action that is referred to.

net, the cube, if in an oblique position, turned and set its fibre equatorial. By suitably breaking and closing the circuit, the cube could be turned 180° round and held in this new position. The axial position of the ligneous fibre was one of unstable equilibrium, from which, if it diverged in the slightest degree right or left, the cube turned and finally set its fibre equatorial. The following is a statement of the results obtained with thirty-five different kinds of wood:—

TABLE I.

Name of wood.	Deportment of mass.	Deportment of structure.	Remarks.
1. Beef-wood	Diamagnetic.	Fibre equatorial.	
2. Black Ebony	"	"	
3. Box-wood	"	"	
4. Second specimen	"	"	
5. Brazil-wood	"	"	
6. Braziletto	"	"	Action decided.
7. Bullet-wood	"	"	Action decided.
8. Cam-wood	"	"	
9. Cocoa-wood	"	"	
10. Coromandel-wood	"	"	Action strong.
11. Green Ebony	"	"	Action strong.
12. Green-heart	"	"	Action strong.
13. Iron-wood	"	"	
14. King-wood	"	"	Action strong.
15. Locust-wood	"	"	
16. Maple	"	"	Action decided.
17. Lance-wood	"	"	Action decided.
18. Olive-tree	"	"	
19. Peruvian-wood	"	"	Action strong.
20. Prince's-wood	"	"	
21. Camphor-wood	"	"	
22. Sandal-wood	"	"	
23. Satin-wood	"	"	
24. Tulip-wood	"	"	
25. Zebra-wood	"	"	
26. Botany Bay Oak	"	"	Action strong.
27. Mazatlan-wood	"	"	Action decided.
28. Tamarind-wood	"	"	
29. Sycamore	"	"	Action decided.
30. Beech	"	"	Action decided.
31. Ruby-wood	"	"	
32. Jacca	"	"	
33. Oak	"	"	Action strong.
34. Yew	"	"	Action feeble.
35. Black Oak	Paramagnetic.	"	Action decided.

The term "decided" is here used to express an action more energetic than ordinary, but in no case does the result lack the decision necessary to place it beyond doubt. It must also be remarked that the term "strong" is used in relation to the general deportment of wood; for, compared with the action of many other diamagnetic bodies, the strongest action of wood is but feeble. Simple as the problem may appear, it required considerable time and care to obtain the results here recorded. During a first examination of the cubes eight anomalies presented themselves—in

eight cases the fibre set either oblique or axial. The whole thirty-five specimens were carefully rescraped with glass and tested once more; still two remained, which, though repelled as masses, persistently set with the fibre axial, and oscillated round this position so steadily as to lead to the supposition that the real deportment of the substance was thus exhibited. I scraped these cubes ten times successively, and washed them with all care, but the deportment remained unchanged. The cubes, for the sake of reference, had been stamped with diminutive numbers by the maker of them; and I noticed at length, that in these two cases a trace of the figures remained: on removing the whole surface which bore the stamp from each, the cubes forsook the axial position, and set, like the others, with the fibre equatorial.

The influence of the mere *form* of an impurity was here very prettily exhibited. The cubes in question had been stamped (probably by an iron tool) with the numbers 33 and 37, which lay in the line of the fibre; the figures, being dumpy little ones, caused an elongation of the magnetic impurity along the said line, and the natural consequence of this elongation was the deportment above described.

Of the thirty-five specimens examined one proved to be paramagnetic. Now, it may be asked, if the views of molecular action stated in the foregoing pages be correct, how is it that this paramagnetic cube sets its fibre equatorial? The case is instructive. The substance (bog oak) had been evidently steeped in a liquid containing a small quantity of iron in solution, whence it derived its magnetism; but here we have no substitution of paramagnetic molecules for diamagnetic ones, as in the cases referred to. The extraneous magnetic constituent is practically indifferent as to the direction of magnetization, and it therefore accommodates itself to the directive action of the wood to which it is attached.

II. ON THE ROTATION OF BODIES BETWEEN POINTED MAGNETIC POLES.

In his experiments on charcoal, wood-bark and other substances, M. PLÜCKER discovered some very curious phenomena of rotation, which occurred on removing the substance experimented on from one portion of the magnetic field to another. To account for these phenomena, he assumed, that in the substances which exhibited the rotation two antagonist forces were perpetually active—a repulsive force, which caused the substance to assume one position; and an attractive force, which caused it to assume a different position: that, of these two forces, the repulsive diminished more quickly than the attractive, when the distance of the body from the poles was augmented. Thus, the former, which was predominant close to the poles, succumbed to the latter when a suitable distance was attained, and hence arose the observed rotation.

Towards the conclusion of the memoir published in the September number of the Philosophical Magazine for 1851, I stated that it was my intention further to examine this highly ingenious theory. I shall now endeavour to fulfil the promise then made, and to state, as briefly as I can, the real law which regulates these complex phenomena.

The masses of soft iron sketched in fig. 1 were placed upon the ends of the electromagnet, with their points facing each other; between the points the body to be examined was suspended by a fine fibre, which, passing round a groove, the substance could be raised or lowered by turning a milled head. The body was first suspended on the level of the points and its deportment noted, it was then slowly elevated, and the change of position, if any, was observed. It was finally permitted to sink below the points and its deportment there noted also.

The following is a statement of the results; the words 'equatorial' (E.) and 'axial' (A.) imply that the longest horizontal dimension of the substance examined took up the position denoted by each of these words respectively. The manner in which the bars were prepared is explained further on.

TABLE II.

Name of substance.	Horizontal dimensions.	Deportment of mass.	Position.		
			Between poles.	Above.	Below.
1. Tartaric acid	0·5 × 0·1	Diamagnetic.	E.	A.	A.
2. A second specimen	0·4 × 0·1	,,	E.	A.	A.
3. Red ferrocyanide of potassium	0·6 × 0·1	Paramagnetic.	A.	E.	E.
4. A second prism	0·9 × 0·12	,,	A.	E.	E.
5. Citric acid	0·55 × 0·25	Diamagnetic.	E.	A.	A.
6. A second specimen	0·48 × 0·2	,,	E.	A.	A.
7. Beryl	0·45 × 0·1	Paramagnetic.	A.	E.	E.
8. Saltpetre	0·6 × 0·3	Diamagnetic.	E.	A.	A.
9. Nitrate of soda	0·6 × 0·12	,,	E.	A.	A.
10. Sulphate of iron	0·7 × 0·15	Paramagnetic.	A.	E.	E.
11. A second specimen	0·6 × 0·03	,,	A.	E.	E.
12. A third specimen	1·0 × 0·13	,,	A.	E.	E.
13. Calcareous spar	0·5 × 0·1	Diamagnetic.	E.	A.	A.
14. A full crystal	....	,,	E.	A.	A.
15. Carbonate of iron	0·5 × 0·1	Paramagnetic.	A.	E.	E.
16. Carbonate of iron powdered and compressed	0·9 × 0·18	,,	A.	E.	E.
17. Compressed disk	0·8 × 0·08	,,	A.	E.	E.
18. Bismuth	0·95 × 0·15	Diamagnetic.	E.	A.	A.
19. The same compressed	0·7 × 0·05	,,	E.	A.	A.
20. The same powdered and compressed	0·6 × 0·07	,,	E.	A.	A.
21. Cylinder of the same	1·0 × 0·15	,,	E.	A.	A.
22. Tourmaline	2·1 × 0·1	Paramagnetic.	A.	E.	E.
23. A second specimen	1·1 × 0·1	,,	A.	E.	E.
24. A third	0·9 × 0·1	,,	A.	E.	E.
25. Sulphate of nickel	0·9 × 0·3	,,	A.	E.	E.
26. A second specimen	0·6 × 0·2	,,	A.	E.	E.
27. Heavy spar	0·38 × 0·18	Diamagnetic.	E.	A.	A.
28. A second specimen	0·4 × 0·18	,,	E.	A.	A.
29. Carbonate of tin powdered and compressed	0·34 × 0·04	,,	E.	A.	A.
30. A second specimen	length 6 times width	,,	E.	A.	A.
31. Ammonio-phosphate of magnesia powdered and compressed	0·3 × 0·06	,,	E.	A.	A.
32. A second specimen	0·5 × 0·07	,,	E.	A.	A.
33. Carbonate of magnesia powdered and compressed	0·45 × 0·04	,,	E.	A.	A.
34. Sulphate of magnesia	0·32 × 0·2	,,	E.	A.	A.
35. A second specimen	0·25 × 0·15	,,	E.	A.	A.
36. Flour compressed	0·24 × 0·04	,,	E.	A.	A.
37. Oxalate of cobalt	0·6 × 0·08	Paramagnetic.	A.	E.	E.

These experiments might be extended indefinitely, but sufficient are here to enable us to deduce the law of action. In the first place we notice, that all those substances which set equatorial between the points, and axial above and below them, are *diamagnetic*; while all those which set axial between the points, and equatorial above and below them, are *paramagnetic*. When any one of the substances here named is reduced to the spherical form, this rotation is not observed. I possess, for example, four spheres of calcareous spar, and when any one of them is suspended between the points, it takes up a position which is not changed when the sphere is raised or lowered; the crystallographic axis sets equatorial in all positions. A sphere of compressed carbonate of iron, suspended between the points, also sets that diameter along which the pressure is exerted from pole to pole, and continues to do so when raised or lowered. A sphere of compressed bismuth, on the other hand, sets its line of compression always equatorial. The position taken up by the spheres depends upon the *molecular structure* of the substances which compose them; but, when the mass is *elongated*, another action comes into play. Such a mass being suspended with its length horizontal, the *repulsion of its ends* constitutes a mechanical couple which increases in power with the length of the mass; and when the body is long enough, and the local repulsion of the ends strong enough, the couple, when it acts in opposition to the directive tendency due to structure, is able to overcome the latter and to determine the position of the mass. In all the cases cited, it was so arranged that the length of the body and its structure should act in opposition to each other. Tartaric acid and citric acid cleave with facility in one direction, and, in the specimens used, the planes of cleavage were perpendicular to the length of the body. In virtue of the structure these planes tended to set equatorial, but the repulsion of the elongated mass by the points prevented this, and caused the planes to set axial. When however the body was raised or lowered out of the sphere of this local repulsion, and into a position where the distribution of the force was more uniform, the advantage due to length became so far diminished that it was overcome, in turn, by the influence of structure, and the planes of cleavage turned into the equatorial position. In the specimen of saltpetre the shortest horizontal dimension was parallel to the axis of the crystal, which axis, when the influence of form is destroyed, always sets equatorial. A full crystal of calcareous spar will, when the magnetic distribution is tolerably uniform, always set its axis at right angles to the line joining the poles; but the axis is the shortest dimension of the crystal, and, between the points, this mechanical disadvantage compels the influence of structure to succumb to the influence of shape. A cube of calcareous spar, in my possession, may be caused to set the optic axis from pole to pole between the points, but this is evidently due to the elongation of the mass along the diagonals; for, when the corner of the cube succeeds in passing the point of the pole, the mass turns its axis with surprising energy into the equatorial position, round which it oscillates with great vivacity. Counting the oscillations, I found that eighty-two were performed by the cube, when its axis was equatorial, in the time

required to perform fifty-nine, when the axis stood from pole to pole. Heavy spar and cœlestine are beautiful examples of directive action. These crystals, as is well known, can be cloven into prisms with rhombic bases: the principal cleavage is parallel to the base of the prism, while the two subordinate cleavages constitute the sides. If a short prism be suspended in a tolerably uniform field of force, so that its rhombic ends shall be horizontal, on exciting the magnet the short diagonal will set equatorial, as shown in fig. 2. If the prism be suspended with its axis and the short diagonal horizontal, the long diagonal being therefore vertical, the short diagonal will retain the equatorial position, while the axis of the prism sets axial as in fig. 3. If the prism be suspended with its long diagonal and axis horizontal, the short diagonal being vertical, and its directive power therefore annulled, the axis will take up the equatorial position, as in fig. 4. Now as the line which sets equatorial in diamagnetic bodies is that in which the magnetic force acts most strongly*, the crystal before us furnishes a perfect example of a substance possessing three rectangular magnetic axes, no two of which are equal. In the experiment cited in Table II., the mass was so cut that the short diagonal of the rhombic base was perpendicular to the length of the specimen. Carbonate of tin, and the other powders, were compressed by placing the powder between two clean plates of copper, and squeezing them together in a strong vice. The line of compression in diamagnetic bodies always sets equatorial, when the field of force is uniform, or approximately so; but between points the repulsion of the ends furnishes a couple strong enough to overcome this directive action, causing the longest dimension of the mass to set equatorial, and consequently its line of compression axial.

Fig. 2.

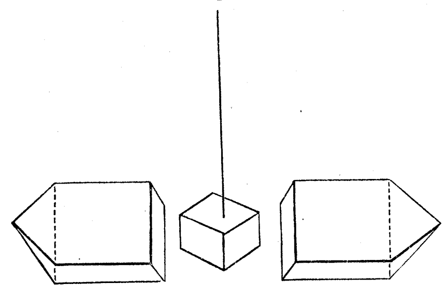


Fig. 3.

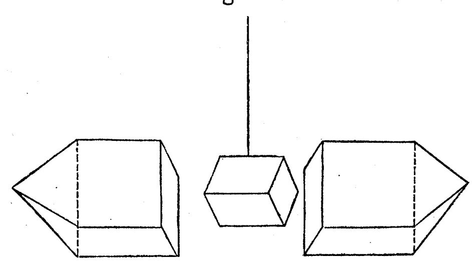
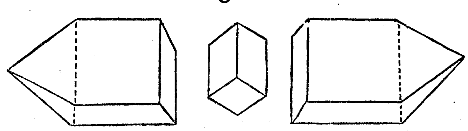


Fig. 4.



The antithesis between the deportment of diamagnetic bodies and of paramagnetic ones is perfect. Between the points the former class set equatorial, the latter axial. Raised or lowered, the former set axial, the latter equatorial. The simple substitution of an attractive for a repulsive force produces this effect. A sphere of ferrocyanide of potassium, for example, always sets the line perpendicular to the crystallographic axis from pole to pole; but when we take a full crystal, whose dimension along its axis, as in one of the cases before us, is six times the dimension at right angles to the axis, the attraction of the ends of such a mass is sufficient to overcome the directive

* Phil. Mag. Ser. 4. vol. ii. p. 177.

action due to structure, and to pull the crystal into the axial position between the points. In a field of uniform force, or between flat poles, the length sets equatorial, and it is the partial attainment of such a field, at a distance from the points, that causes the crystal to turn from axial to equatorial when it is raised or lowered. Beryl is a paramagnetic crystal, and when the influence of form is annulled, it always sets a line perpendicular to the axis of the crystal from pole to pole; a cube of this crystal, at present in my possession, shows this deportment whether the poles are pointed or flat; but in the specimen examined the dimension of the crystal along its axis was greatest, and hence the deportment described. It is needless to dwell upon each particular paramagnetic body: the same principle was observed in the preparation and choice of all of them; namely, that the line which, in virtue of the internal structure of the substance, would set axial, was transverse to the length of the body. The directive action due to structure was thus brought into opposition with the tendency of magnetic bodies to set their longest dimension from pole to pole: between the points the latter tendency was triumphant; at a distance, on the contrary, the influence of structure prevailed. The substance which possesses this directive action in the highest degree is carbonate of iron: when a lozenge, cloven from the crystalline mass, is suspended from the angle at which the crystallographic axis issues, there is great difficulty in causing the plate to set axial. If the points are near, on exciting the magnetism the whole mass springs to one or the other of the points; and when the points are distant, the plate, although its length may be twenty times its thickness, will set strongly equatorial. An excitation by one cell was sufficient to produce this result. In the experiment cited the residual magnetism was found to answer best, as it permitted the ends of the plate to be brought so near to the points that the mass was pulled into the axial position. When the magnet was more strongly excited, and the plate raised so far above the points as to prevent its springing to either of them, it was most interesting to watch the struggle of the two opposing tendencies. Neither the axial nor the equatorial position could be retained; the plate would wrench itself spasmodically from one position into the other, and, like the human spirit operated on by conflicting passions, find rest nowhere.

The conditions which determine the curious effects described in the present chapter may be briefly expressed as follows:—

An elongated diamagnetic body being suspended in the magnetic field, if the shortest horizontal dimension tend, in virtue of the internal structure of the substance, to set equatorial, it is opposed by the tendency of the longest dimension to take up the same position. Between the pointed poles the influence of length usually predominates; above the points and below them the directive action due to structure prevails.

Hence, the rotation of such a diamagnetic body, on being raised or lowered, is always from the equatorial to the axial position.

If the elongated mass be magnetic, and the shortest dimension of the mass tend,

in virtue of its structure, to set from pole to pole, it is opposed by the tendency of the longest dimension to take up the same position. Between the points the influence of length is paramount, above and below the points the influence of structure prevails.

Hence, the rotation of magnetic bodies, on being raised or lowered, is always from the axial to the equatorial position.

The error of the explanation which referred many of the above actions to the presence of two conflicting forces, one of which diminished with the distance in a quicker ratio than the other, lies in the supposition, that the assuming of the axial position proved a body to be magnetic, while the assuming of the equatorial position proved a body to be diamagnetic. This assumption was perfectly natural in the early stages of diamagnetic research, when the modification of magnetic force by structure was unknown. Experience however proves that the total mass of a magnetic body continues to be attracted after it has assumed the equatorial position, while the total mass of a diamagnetic body continues to be repelled after it has taken up the axial one.

III. ON THE DISTRIBUTION OF THE MAGNETIC FORCE BETWEEN TWO FLAT POLES.

In experiments where a uniform distribution of the magnetic force is desirable, flat poles, or magnetized surfaces, have been recommended. It has long been known that the force proceeds with great energy from the edges of such poles: the increase of force from the centre to the edge has been made the subject of a special investigation by M. VON KOLKE*. The central portion of the magnetic field, or space between two such magnetized surfaces, has hitherto been regarded as almost perfectly uniform, and indeed for all ordinary experiments the uniformity is sufficient. But, when we examine the field carefully, we find that the uniformity is not perfect. Substituting, for the sake of convenience, the edge of a pole for a point, I studied the phenomena of rotation described in the last section, in a great number of instances, by comparing the deportment of an elongated body, suspended in the centre of the space between two flat poles, with its deportment when suspended between the top or the bottom edges. Having found that the fibre of wood, in masses where form had no influence, always set equatorial, I proposed to set this tendency to contend with an elongation of the mass in a direction at right angles to the fibre. For this purpose thirty-one little wooden bars were carefully prepared and examined, the length of each bar being about twice its width, and the fibre coinciding with the latter dimension. The bars were suspended from an extremely fine fibre of cocoon silk, and in the centre of the magnetic field each one of them set its length axial and consequently its fibre equatorial. Between the top and bottom edges, on the contrary, each piece set its longest dimension equatorial, and, consequently, the fibre axial.

For some time I referred the axial setting of the mass, in the centre of the field, to

* POGGENDORFF's Annalen, vol. lxxxi. p. 321.

the directive action of the fibre, though, knowing the extreme feebleness of this directive action, I was surprised to find it able to accomplish what the experiments exhibited. The thought suggested itself, however, of suspending the bars with the fibre vertical, in which position the latter could have no directive influence. Here also, to my surprise, the directive action, though slightly weakened, was the same as before; in the centre of the field the bars took up the axial position. Bars of sulphur, wax, salt of hartshorn, and other diamagnetic substances were next examined: they all acted in the same manner as the wood, and thus showed that the cause of the rotation lay, not in the structure of the substances, but in the distribution of the magnetic force around them. This distribution in fact was such, that the straight line which connected the centre of one pole with that of the opposite one was the line of weakest force. OHM represents the distribution of electricity upon the surfaces of conductors by regarding the tensions as ordinates, and erecting them from the points to which they correspond, the steepness of the curve formed by uniting the ends of the ordinates being the measure of the increase or diminution of tension. Taking the centre of the magnetic field as the origin, and drawing lines axial and equatorial; if we erect the magnetic tensions along these lines, we shall find a steeper curve in the equatorial than in the axial direction. This may be proved by suspending a bit of carbonate of iron in the centre of the magnetic field; on exciting the magnet, the suspended body will not move to the nearest portion of the flat pole, though it may be not more than a quarter of an inch distant, but will move equatorially towards the edges, though they may be two inches distant. The little diamagnetic bars referred to were therefore pushed into the axial position by the force acting with superior power in an equatorial direction.

The results just described are simply due to the recession of the ends of an elongated body from places of stronger to those of weaker force; but it is extremely instructive to observe how this result is modified by structure. If, for example, a plate of bismuth be suspended between the poles with the plane of principal cleavage vertical, the plate will assert the equatorial position from top to bottom; and in the centre with almost the same force as between the edges. The cause of this lies in the structure of the bismuth. Its position in the field depends not so much upon the distribution of the magnetic force around it, as upon the direction of the force *through* it. I will not, however, anticipate matters by entering further upon this subject at present.

IV. COMPARATIVE VIEW OF PARAMAGNETIC AND DIAMAGNETIC PHENOMENA.

1. *State of Diamagnetic Bodies under magnetic influence.*

When a piece of soft iron is brought near to a magnet, it is attracted by the latter: this attraction is not the act of the magnet alone, but results from the mutual action of the magnet and the body upon which it operates. The soft iron in this case is said to be magnetized by influence; it becomes itself a magnet, and the intensity of

its magnetization varies with the strength of the influencing magnet. POISSON figured the act of magnetization as consisting of the decomposition of a neutral magnetic fluid into north and south magnetism, the amount of the decomposition being proportional to the strength of the magnet which produces it. AMPÈRE, discarding the notion of magnetic fluids, figured the molecules of soft iron as surrounded by currents of electricity, and conceived the act of magnetization to consist in setting the planes of these molecular currents parallel to each other: the degree of parallelism, or in other words, the intensity of the magnetization, depending, as in POISSON's hypothesis, upon the strength of the influencing magnet.

The state into which the soft iron is here supposed to be thrown is a state of constraint, and when the magnet is removed, the substance returns to its normal condition. POISSON's separated fluids rush together once more, and AMPÈRE's molecular currents return to their former irregular positions. As our knowledge increases, we shall probably find both hypotheses inadequate to represent the phenomena; the only thing certain is, that the soft iron, when acted upon by the magnet, is thrown into an unusual condition, in virtue of which it is attracted; and that the intensity of this condition is a function of the force which produces it.

There are, however, certain bodies which, unlike soft iron, offer a great resistance to the imposition of the magnetic state, but when once they are magnetized they do not, on the removal of the magnet, return to their neutral condition, but on the contrary retain the magnetism impressed on them. It is in virtue of this quality that steel can be formed into compass needles and permanent magnets. This power of resistance and retention is named by POISSON coercive force.

Let us conceive a body already magnetized, and in which coercive force exists in a very high degree—a piece of very hard steel for example—to be brought near a magnet, the strength of which is not sufficient to magnetize the steel further. To simplify the matter let us fix our attention upon the south pole of the magnet, and conceive it to act upon the north pole of the piece of steel. Let the magnetism of the said south pole, referred to any unit, be M, and of the north pole of the steel, M′; then their mutual attraction, at the unit of distance, is expressed by the product MM′. Conceive now the magnet to increase in power from M to nM, the steel being still supposed hard enough to resist magnetization by influence; the mutual attraction now will be

$$n\mathrm{MM}',$$

or n times the former attraction; hence when a variable magnetic pole acts on an opposite one of constant power, the attraction is proportional to the strength of the former.

Let us now take a body whose magnetization varies with that of the magnet: a south pole of the strength M induces in such a body a north pole of the strength M′, and the attraction which results from their mutual action is

$$\mathrm{MM}'.$$

Let the strength of the influencing south pole increase from M to nM; then, assuming the magnetism of the body under influence to increase in the same ratio, the strength of the above-mentioned north pole will become $n\mathrm{M}'$, and the attraction, expressed by the product of both, will be

$$n^2\mathrm{MM}';$$

that is to say, the attraction of a body magnetized by influence, and whose magnetism varies as the strength of the influencing magnet, is proportional to the *square of the strength* of the latter.

Here then is a mark of distinction between those bodies which have their power of exhibiting magnetic phenomena conferred upon them by the magnet, and those whose actions are dependent upon some constant property of the mass: in the latter case the resultant action will be simply proportional to the strength of the magnet, while in the former case a different law of action will be observed*.

The examination of this point lies at the very foundation of our inquiries into the nature of the diamagnetic force. Is the repulsion of diamagnetic bodies dependent merely on the mass considered as ordinary matter, or is it due to some condition impressed upon the mass by the influencing magnet? This question admits of the most complete answer either by comparing the increase of repulsion with the increase of power in the magnet which produces the repulsion, or by comparing the attraction of a paramagnetic body, which we know to be thrown into an unusual condition, with the repulsion of a diamagnetic body, whose condition we would ascertain.

Bars of iron and bismuth, of the same dimensions, were submitted to the action of an electromagnet, which was caused gradually to increase in power; commencing with an excitation by one cell, and proceeding up to an excitation by ten or fifteen. The strength of the current was in each case accurately measured by a tangent galvanometer. The bismuth bar was suspended between the two flat poles, and, when the magnet was excited, took up the equatorial position. The iron bar, if placed directly between the poles, would, on the excitation of the magnetism, infallibly spring to one of them; hence it was removed to a distance of 2 feet 7 inches from the centre of the space between the poles, and in a direction at right angles to the line which united them. The magnet being excited, the bar was drawn a little aside from its position of equilibrium and then liberated, a series of oscillations of very small amplitude followed, and the number of oscillations accomplished in a minute was carefully ascertained. Tables III. and IV. contain the results of experiments made in the manner described with bars of iron and bismuth of the same dimensions.

* This test was first pointed out in a paper on the Polarity of Bismuth, Phil. Mag. Nov. 1851, p. 333. I have reason, however, to know that the same thought occurred to M. Poggendorff previous to the publication of my paper.—J. T.

TABLE III.

Bar of soft iron, No. 1.
length 0·8 of an inch.
width 0·13 of an inch.
depth 0·15 of an inch.

Strength of current.	Attraction.
168	168^2
214	204^2
248	253^2
274	275^2
323	313^2
362	347^2
385	374^2
411	385^2

TABLE IV.

Bar of bismuth, No. 1.
length 0·8 of an inch.
width 0·13 of an inch.
depth 0·15 of an inch.

Strength of current.	Repulsion.
78	78^2
136	135^2
184	191^2
226	226^2
259	259^2
287	291^2
341	322^2
377	359^2
411	386^2

These experiments prove, that, up to a strength of about 280, the attractive force operating upon the iron, and the repulsive force acting upon the bismuth, are each accurately proportional to the square of the strength of the magnetising current. For higher powers, both attraction and repulsion increase in a smaller ratio; but it is here sufficient to show that the diamagnetic repulsion follows precisely the same law as the magnetic attraction. So accurately indeed is this parallelism observed, that while the forces at the top of the tables produce attractions and repulsions exactly equal to the square of the strength of the current, the same strength of 411, at the bottom of both tables, produces in iron an attraction of 385^2, and in bismuth a repulsion of 386^2. The numbers which indicate the strength of current in the first column are the

tangents of the deflections observed in each case: neglecting the indices, the figures in the second column express the number of oscillations accomplished in a minute, multiplied by a constant factor to facilitate comparison: the forces operating upon the bars being proportional to the squares of the number of oscillations, the simple addition of the index figure completes the expression of these forces.

In these experiments the bismuth bar set *across* the lines of magnetic force, while the bar of iron set *along* them; the former was so cut from the crystalline mass, that the plane of principal cleavage was parallel to the length of the bar, and in the experiments hung vertical. I thought it interesting to examine the deportment of a bar of bismuth which should occupy the same position, with regard to the lines of force, as the bar of iron; that is to say, which should set its length axial. Such a bar is obtained when the planes of principal cleavage are transverse to the length.

TABLE V.

Bar of bismuth, No. 2.
length 0·8 of an inch.
width 0·13 of an inch.
depth 0·15 of an inch.

Set axial between the excited poles.

Strength of current.	Repulsion.
68	67^2
182	187^2
218	218^2
248	249^2
274	273^2
315	309^2
364	350^2
401	366^2

A deportment exactly similar to that exhibited in the foregoing cases is observed here also: up to about 280 the repulsions are accurately proportional to the squares of the current strengths, and from this point forward they increase in a less ratio.

A paramagnetic substance was next examined which set its length at right angles to the lines of magnetic force: the substance was carbonate of iron. The native crystallized mineral was reduced to powder in a mortar, and the powder was compressed. It was suspended, like the bismuth, between the flat poles, with its line of compression horizontal. When these poles were excited the compressed bar set the line of pressure from pole to pole, and consequently its length equatorial.

Table VI.

Bar of compressed carbonate of iron.
length 0·95 of an inch.
width 0·17 of an inch.
depth 0·23 of an inch.
Set equatorial between the excited poles.

Strength of current.	Attraction.
74	74^2
135	133^2
179	180^2
214	218^2
249	248^2
277	280^2
341	330^2
381	353^2

It is needless to remark upon the perfect similarity of deportment here exhibited to the cases previously recorded.

In the following instances the same law of increase is observable.

Table VII.

Sulphate of iron, No. 1.
length 0·75 of an inch.
width 0·22 of an inch.
depth 0·27 of an inch.
Set axial between the excited poles.

Strength of current.	Attraction.
71	70^2
132	133^2
217	220^2
280	275^2
328	333^2
359	348^2

Table VIII.

Sulphate of iron, No. 2.
length 0·75 of an inch.
width 0·22 of an inch.
depth 0·27 of an inch.
Set equatorial between the excited poles.

Strength of current.	Attraction.
70	68^2
121	123^2
203	207^2
271	268^2
331	308^2
370	334^2

In sulphate of iron there is one direction which, in virtue of the molecular structure of the substance, sets strongly from pole to pole. The bar No. 1. was so cut that this direction was parallel to its length, which therefore set axial; while No. 2. had the same direction *across* it, thus causing the length of the bar to set equatorial.

Two comparative series were finally made with two prisms of iron and of bismuth, more massive than those previously examined.

Table IX.

Bar of iron, No. 2.
length 1·0 inch.
width 0·3 inch.
depth 0·3 inch.

Strength of current.	Attraction.
70	71^2
122	122^2
167	168^2
206	204^2
268	260^2
322	311^2
356	339^2

Table X.

Bar of bismuth, No. 3.
length 1·0 inch.
width 0·3 inch.
depth 0·3 inch.

Strength of current.	Repulsion.
70	72^2
126	121^2
164	166^2
206	205^2
246	248^2
276	279^2
364	344^2

These experiments can leave little doubt upon the mind, that if a magnetic body be attracted in virtue of its being converted into a magnet, a diamagnetic body is repelled *in virtue of its being converted into a diamagnet.* On no other assumption can it be explained, why the repulsion of the diamagnetic body, like the attraction of the magnetic one, increases in a so much quicker ratio than the force of the magnet which produces the repulsion. But, as this is a point of great importance, I will here introduce corroborative evidence, derived from modes of experiment totally different from the method already described. By a series of measurements with the torsion balance, in which the attractive and repulsive forces were determined directly, with the utmost care, the relation of the strength of the magnet to the force acting upon the substances named in Tables XI., XII. and XIII. was found to be as follows:—

TABLE XI.

Spheres of native sulphur.

Strength of magnet.	Ratio of repulsions.
96	95^2
153	158^2
222	224^2
265	264^2
316	316^2

TABLE XII.

Spheres of carbonate of lime.

Strength of magnet.	Ratio of repulsions.
134	134^2
172	173^2
213	212^2
259	264^2
310	311^2
370	374^2

TABLE XIII.

Spheres of carbonate of iron.

Strength of magnet.	Ratio of attractions.
66	66^2
89	89^2
114	114^2
141	141^2

In confirmation of these results I will cite a series obtained by M. E. BECQUEREL*,

* Ann. de Chim. et de Phys. 3rd Series. vol. xxviii. p. 302.

whose experiments first showed that the repulsion of diamagnetic bodies follows the same law as the attraction of magnetic ones.

Bar of sulphur.
length 25 millims.
weight 840 milligrms.

Squares of the magnetic intensities.	Quotients of the repulsions by the magnetic intensities.
36·58	0·902
27·60	0·929
26·84	0·906
16·33	0·920

The constancy of the quotient in the second column proves that the ratio of the repulsions to the squares of the magnetic intensities is a ratio of equality.

I will also cite a series of experiments by Mr. JOULE *, which he adduces in confirmation of the results obtained by M. E. BECQUEREL and myself.

Bar of bismuth.

Strength of magnet.	Repulsions.
1	1^2
2	2^2
4	4^2

Let us contrast these with the results obtained by the same gentleman, by permitting the magnet to act upon a hard magnetic needle.

Magnetic needle.
length 1·5 inch.

Strength of magnet.	Attraction.
1	1
2	2
4	4

Here we find experiment in strict accordance with the theoretical deduction stated at the commencement of the present chapter. The intensity of the magnetism of the steel needle is constant, for the steel resists magnetization by influence; the consequence is that the attraction is simply proportional to the strength of the magnet.

A consideration of the evidence thus adduced from independent sources, and obtained by different methods, must, I imagine, render the conclusion certain that diamagnetic bodies, like magnetic ones, exhibit their phenomena in virtue of a state

* Phil. Mag. 4th Series. vol. iii. p. 32.

of magnetization induced in them by the influencing magnet. This conclusion is in no way invalidated by the recent researches of M. PLÜCKER, on the law of induction in paramagnetic and diamagnetic bodies, but on the contrary derives support from his experiments. With current strengths which stand in the ratio of 1 : 2, M. PLÜCKER finds the repulsion of bismuth to be as 1 : 3·62, which, though it falls short of the ratio of 1 : 4, as the law of increase according to the square of the current would have it, is sufficient to show that the bismuth was not passive, but acted the part of an induced diamagnet in the experiments. In the case of the soft iron itself M. PLÜCKER finds a far greater divergence; for here currents which stand in the ratio of 1 : 2 produce attractions only in the ratio of 1 : 2·76.

2. *Duality of Diamagnetic Excitement.*

Having thus safely established the fact, that diamagnetic bodies are repelled, in virtue of a certain state into which they are cast by the influencing magnet, the next step of our inquiry is;—Will the state evoked by one magnetic pole facilitate, or prevent, the repulsion of the diamagnetic body by a second pole of an opposite quality? If the force of repulsion were an action on the mass, considered as ordinary matter, this mass, being repelled by both the north and the south pole of a magnet, when they operate upon it separately, ought to be repelled by the sum of the forces of the two poles where they act upon it together. But if the excitation of diamagnetic bodies be of a *dual* nature, as is the case with magnetic bodies, then it may be expected, that the state excited by one pole will not facilitate, but on the contrary prevent, the repulsion of the mass by a second opposite pole.

To solve this question the apparatus sketched in fig. 5*a*. Plate II. was made use of. AB and CD are two helices of copper wire 12 inches long, of 2 inches internal, and of 5½ inches external diameter. Into them fit soft iron cores 2 inches thick: the cores are bent as in the figure, and reduced to flat surfaces along the line *ef*, so that when the two semicylindrical ends are placed together, they constitute a cylinder of the same diameter as the cores within the helices*. In front of these poles a bar of pure bismuth *gh* was suspended by cocoon silk; by imparting a little torsion to the fibre, the end of the bar was caused to press gently against a plate of glass *ik*, which stood between it and the magnets. By means of a current reverser the polarity of one of the cores could be changed at pleasure; thus it was in the experimenter's power to excite the cores, so that the poles PP′ should be of the same quality, or of opposite qualities.

The bar, being held in contact with the glass by a very feeble torsion, a current was sent round the cores, so that they presented two poles of the same name to the suspended bismuth; the latter was promptly repelled, and receded to the position dotted in the figure. On interrupting the current it returned to the glass as before.

* The ends of the semicylinders were turned so as to present the blunted apex of a cone to the mass of bismuth.

The cores were next excited, so that two poles of opposite qualities acted upon the bismuth; the latter remained perfectly unmoved*.

This experiment shows that the state, whatever it may be, into which bismuth is cast by one pole, so far from being favourable to the action of the opposite pole, completely neutralizes the effect of the latter. A perfect analogy is thus established between the deportment of the bismuth and that of soft iron under the same circumstances; for it is well known that a similar neutralization occurs in the latter case. If the repulsion depended upon the *abstract strength* of the poles, without reference to their *quality*, the repulsion, when the poles are of opposite names, ought to be *greater* than when they are alike; for in the former case the poles are greatly strengthened by their mutual inductive action, while, in the latter case, they are enfeebled by the same cause. But the fact of the repulsion being dependent on the quality of the pole, demonstrates that the substance is capable of assuming a condition peculiar to each pole, or in other words, is capable of a *dual* excitation†. The experiments from which these conclusions are drawn are a manifest corroboration of those made by M. Reich with steel magnets.

If we suppose the flat surfaces of the two semicylinders which constitute the ends of the cores to be in contact, and the cores so excited that the poles P and P′ are of different qualities, the arrangement, it is evident, forms a true electro-magnet of the horseshoe form; and here the pertinency of a remark made by M. Poggendorff, with his usual clearness of perception, becomes manifest; namely, that if the repulsion of diamagnetic bodies be an indifferent one of the mass merely, there is no reason why they should not be repelled by the centre of a magnet, as well as by its ends.

3. *Separate and joint action of a Magnet and a Voltaic Current on Paramagnetic and Diamagnetic Bodies.*

In operating upon bars of bismuth with the magnet, or the current, or both combined, it was soon found that the gravest mistakes might be committed, if the question of structure was not attended to; that it is not more indefinite to speak of the volume of a gas without giving its temperature, than to speak of the deportment of bismuth without stating the relation of the form of the mass to the planes of crystallization. Cut in one direction, a bar of bismuth will set its length parallel to an electric current passing near it; cut in another direction, it will set its length perpendicular

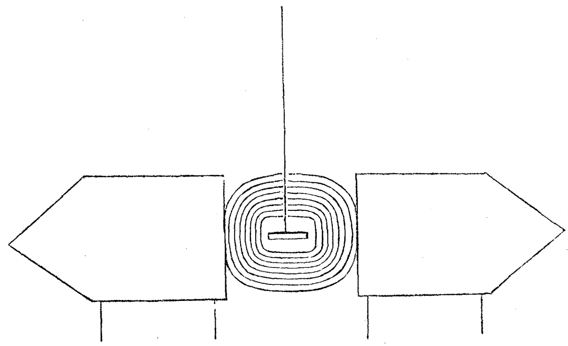
* A shorter bar of bismuth than that here sketched, with a light index attached to it, makes the repulsion more evident. It may be thus rendered visible throughout a large lecture-room.

† Since the above was written, the opinion has been expressed to me, that the action of the *unlike* poles, in the experiment before us, is "diverted" from the bismuth upon each other, the absence of repulsion being due to this diversion, and not to the neutralization of inductions in the mass of the bismuth itself. Many, however, will be influenced by the argument as stated in the text, who would not accept the interpretation referred to in this note; I therefore let the argument stand, and hope at no distant day to return to the subject.—J. T., 5th May, 1855.

to the same current. It was necessary to study the deportment of both of these bars separately.

A helix was formed of covered copper wire one-twentieth of an inch thick: the space within the helix was rectangular, and was 1 inch long, 0·7 inch high, and 1 inch wide: the external diameter of the helix was 3 inches. Within the rectangular space the body to be examined was suspended by a fibre which descended through a slit in the helix. The latter was placed between the two flat poles of an electro-magnet, and could thus be caused to act upon the bar within it, either alone or in combination with the magnet. The disposition will be at once understood from fig. 6, which gives a front view of the arrangement.

Fig. 6.



Action of Magnet alone: division of Bars into Normal and Abnormal.—A bar of soft iron suspended in the magnetic field will set its longest dimension from pole to pole: this is the normal deportment of paramagnetic bodies. A bar of bismuth, whose planes of principal cleavage are throughout parallel to its length, suspended in the magnetic field with the said planes vertical, will set its longest dimension at right angles to the line joining the poles: this is the normal deportment of diamagnetic bodies. We will therefore, for the sake of distinction, call the former a *normal paramagnetic bar*, and the latter a *normal diamagnetic bar*.

A bar of compressed carbonate of iron dust, whose shortest dimension coincides with the line of pressure, will, when suspended in the magnetic field with the said line horizontal, set its length equatorial. A bar of compressed bismuth dust, similarly suspended, or a bar of bismuth whose principal planes of crystallization are transverse to its length, will set its length axial in the magnetic field. We will call the former of these an *abnormal paramagnetic bar*, and the latter an *abnormal diamagnetic bar*.

Action of Current alone on normal and abnormal bars.—A normal paramagnetic bar was suspended in the helix above described; when a current was sent through the latter, the bar set its longest horizontal dimension parallel to the axis of the helix, and consequently perpendicular to the coils.

An *abnormal paramagnetic bar* was suspended in the same manner; when a current was sent through the helix, the bar set its longest dimension perpendicular to the axis of the helix, and consequently parallel to the coils.

A *normal diamagnetic bar* was delicately suspended in the same helix; on the passage of the current it acted precisely as the abnormal magnetic bar; setting its longest dimension perpendicular to the axis of the helix and parallel to the coils.

When a fine fibre and sufficient power are made use of, this deportment is obtained without difficulty.

An *abnormal diamagnetic bar* was suspended as above; on the passage of the current it acted precisely as the normal magnetic bar; it set its length parallel to the axis of the helix and perpendicular to the coils. Here also, by fine manipulation, the result is obtained with ease and certainty.

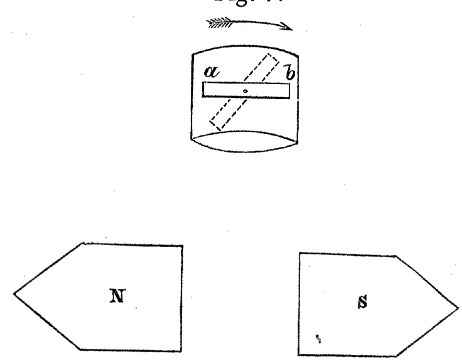
Action of Magnet and Current combined.—In examining this subject eight experiments were made with each particular bar; it will be remembered that fig. 6 gives a general view of the arrangement.

1. Four experiments were made in which the *magnet* was excited first, and after the suspended bar had taken up its position of equilibrium, the deflection produced by the passage of a current through the surrounding helix was observed.

2. Four experiments were made in which the *helix* was excited first, and when the bar within it had taken up its position of equilibrium, the magnetism was developed and the consequent deflection observed.

Normal Paramagnetic Bar.—In experimenting with the soft iron it was necessary to place it at some distance from the magnet; otherwise the attraction of the entire mass by one or the other pole would completely mask the action sought. Fig. 7 represents the disposition of things in these experiments: N and S indicate the north and south poles of the magnet; *ab* is the bar of iron; the helix within which the bar was suspended is shown in outline around it; the arrow shows the direction of the current in the *upper half* of the helix; its direction in the under portion would, of course, be the reverse.

Fig. 7.

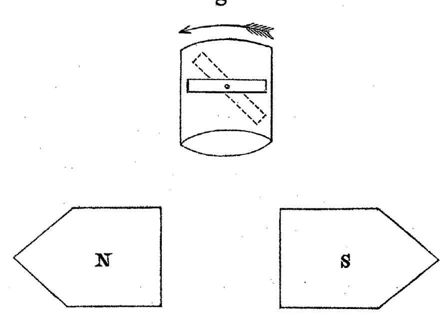


On exciting the magnet, the bar of soft iron set itself parallel to the line joining the poles, as shown by the unbroken line in fig. 7.

When the direction of the current in the helix was that indicated by the arrow, the bar was deflected towards the position dotted in the figure.

Interrupting the current in the helix, and permitting the magnet to remain excited, the bar returned to its former position: the current was now sent through the helix in the direction of the arrow, fig. 8; the consequent deflection was towards the dotted position.

Fig. 8.



Both the current which excited the magnet and that which passed through the

helix were now interrupted, and the polarity of the magnet was reversed. On sending a current through the helix in the direction of the arrow, the deflection of the bar was from the position of the defined line to that of the dotted one, fig. 9.

Fig. 9.

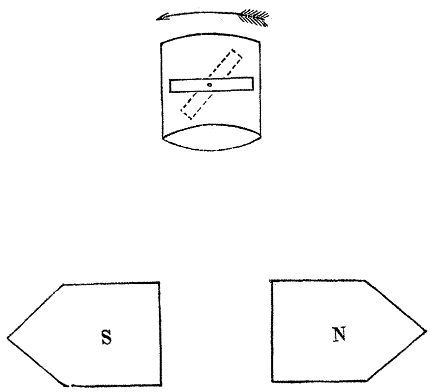
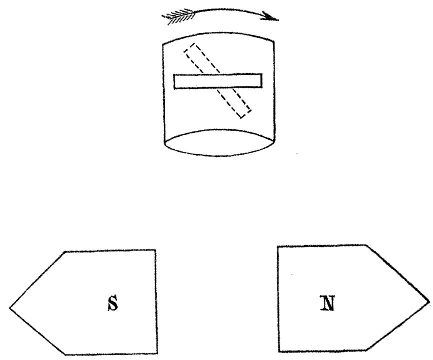


Fig. 10.



Interrupting the current through the helix, and permitting the bar to come to rest under the influence of the magnet alone, a current was sent through the helix in a direction opposed to its former one: the deflection produced was that shown in fig. 10.

The position of equilibrium finally assumed by the bar depends, of course, upon the ratio of the forces acting upon it: in these experiments, the bar, in its final position, enclosed an angle of about 50 degrees with the axial line.

A series of experiments were next made, in which the bar was first acted on by the current passing through the helix, the magnet being brought to bear upon it afterwards. On the passage of the current through the helix, in the direction shown in fig. 11, the bar set its length parallel to the axis of the latter. On exciting the magnet so that its polarity was that indicated by the letters N and S in the figure, the deflection was towards the dotted position.

Fig. 11.

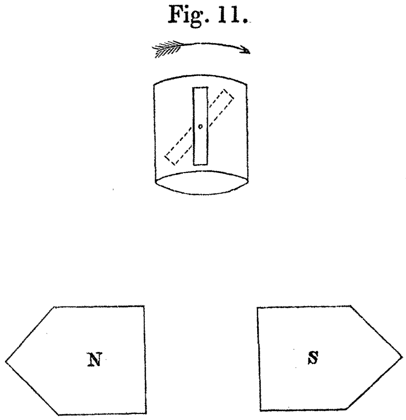
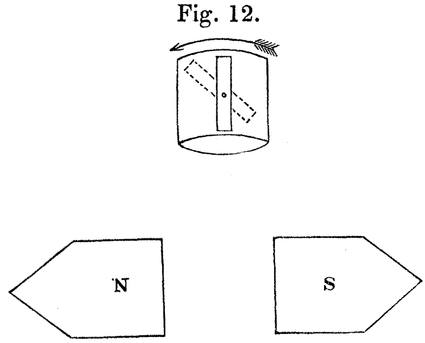


Fig. 12.



Interrupting the current through both magnet and helix, and reversing the current through the latter, the bar came to rest, as before, parallel to the axis: on exciting the magnet, as in the last case, the deflection was that shown in fig. 12.

Preserving the same current in the helix, and reversing the polarity of the magnet, the deflection was that shown in fig. 13.

Preserving the magnet poles as in the last experiment, and reversing the current in the helix, the deflection was that shown in fig. 14.

Fig. 13.

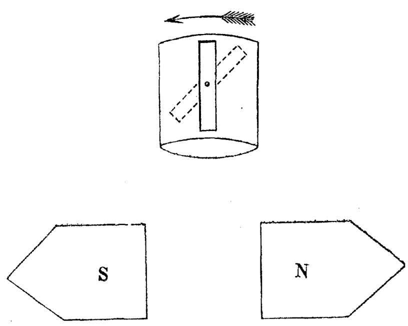
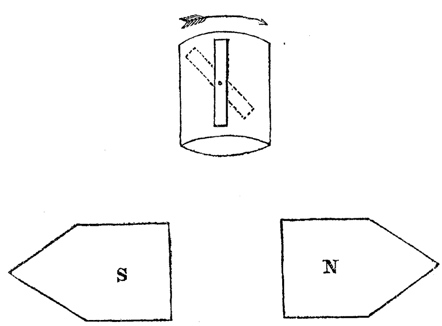


Fig. 14.



In these cases, the bar, in its final position of equilibrium, enclosed an angle of about 40 degrees with the axial line.

Normal Diamagnetic Bar.—The above experiments exhibit to us the deportment of the normal paramagnetic body under a great variety of conditions, and our next step is to compare with it the deportment of the normal diamagnetic body under the same circumstances.

For the sake of increasing the force, the helix was removed from its lateral position and placed between the two poles, as in fig. 6, p. 25. The normal diamagnetic bar was suspended within the helix and submitted to the self-same mode of examination as that applied in the case of the paramagnetic body.

The polarity first excited was that shown in fig. 9, Plate I., and the position of rest, when the magnet alone acted, was at right angles to the line joining the poles; on sending a current through the helix in the direction of the arrow, the deflection was towards the dotted line.

Preserving the magnetic polarity as in the last experiment, the direction of the current through the helix was reversed, and the deflection was that shown in fig. 10.

Reversing the polarity of the magnet, and sending the current through the helix in the direction of the last experiment, the deflection was that shown in fig. 11.

Preserving the last magnetic poles, and sending the current through the helix in the opposite direction, the deflection was that shown in fig. 12.

In the following four experiments the helix was excited first.

Operated upon by the helix alone, the suspended bar set its length parallel to the convolutions, and perpendicular to the axis of the coil: the direction of the current was first that shown in fig. 13: when the magnet was excited, the bar was deflected towards the dotted position.

Interrupting both currents, and reversing the current in the helix; when the magnet was excited, as in the last experiment, the deflection was that shown in fig. 14.

Preserving the helix current as in the last experiment; when the polarity of the magnet was reversed, the deflection was that shown in fig. 15.

Interrupting both, and reversing the current in the helix; when the magnet was excited as in the last experiment, the deflection was that shown in fig. 16.

In a paper on the Polarity of Bismuth* published in the Philosophical Magazine, Ser. 4. vol. ii., and in POGGENDORFF's Annalen, vol. lxxxvii., an experiment is recorded in which the deportment exhibited by fig. 11 of the present series was obtained. In a recent memoir on the same subject, M. v. FEILITSCH† states that he has sought this result in vain. Sometimes he observed the deflection at the moment of closing the circuit, but conceived that it must be ascribed to the action of induced currents; for immediately afterwards a deflection in the opposite direction was observed, which deflection proved to be the permanent one.

I have repeated the experiment here referred to with all possible care; and the result is that described in the remarks which refer to fig. 11. This result agrees in all respects with that described in my former paper. To enable myself, however, to appeal to quantitative measurement, a small graduated circle was constructed and placed underneath the bar of bismuth suspended within the helix. The effect, as will be seen, is not one regarding which a mistake could be made on account of its minuteness: operating delicately, and choosing a suitable relation between the strength of the magnet and that of the spiral‡, on sending a current through the latter as in fig. 11, the bar was deflected so forcibly that the limit of its first impulsion reached 120° on the graduated circle underneath. The permanent deflection of the bar amounted to 60° in the same direction, and hence the deportment could in no wise be ascribed to the action of induced currents, which vanish immediately. Before sending the current through the helix, the bar was acted on by the magnet alone, and pointed to zero.

Though it was not likely that the shape of the poles could have any influence here, I repeated the experiment, using the hemispherical ends of two soft iron cores as poles: the result was the same.

A pair of poles with the right and left hand-edges rounded off showed the same deportment.

A pair of poles presenting chisel edges to the helix showed the same deportment.

Various other poles were made use of, some of which appeared to correspond exactly with those figured by M. v. FEILITSCH; but no deviation from the described deportment was observed. To test the polarity of the magnet, a magnetic needle was always at hand: once or twice the polarity of the needle became reversed, which, had it not been noticed in time, would have introduced confusion into the experiments.

* From the notices of this paper which have appeared in the continental journals, I am obliged to infer that it is in some respects obscurely written. The conclusion I intended to express is that bismuth possesses a polarity opposed to that of iron.—J. T.

† POGGENDORFF's Annalen, vol. xcii. p. 395.

‡ In most of these experiments the spiral was excited by ten cells, the magnet by two.

Here is a source of error, against which, however, M. v. FEILITSCH has probably guarded himself. Some irregularity of crystalline structure may, perhaps, have influenced the result. With "chemically pure zinc" M. v. FEILITSCH obtained the same deflection that I obtained with bismuth: now chemically pure zinc is *diamagnetic**, and hence its deportment is corroborative of that which I have observed. M. v. FEILITSCH, however, appears to regard the zinc used by him as magnetic; but if this be the case it cannot have been chemically pure. It is necessary to remark that I have called the north pole of the electro-magnet that which attracts the south, or unmarked end, of a magnetic needle; and I believe this is the custom throughout Germany.

Abnormal Paramagnetic Bar.—This bar consisted of compressed carbonate of iron dust, and was suspended within the helix with the line of compression, which was its shortest dimension, horizontal. As in the cases already described, it was first acted upon by the magnet alone; having attained its position of equilibrium, a current was sent through the helix, and the subsequent deflection was observed.

The magnet being excited as in fig. 17, Plate I., the bar set its length equatorial; on sending a current through the helix in the direction of the arrow, the bar was deflected to the dotted position.

Reversing the current in the helix, but permitting the magnet to remain as before, the deflection was that shown in fig. 18.

Interrupting all, and reversing the polarity of the magnet; on sending the current through as in the last case, the deflection was that shown in fig. 19.

Reversing the current, but preserving the last condition of the magnet, the deflection was that shown in fig. 20.

In the subsequent four experiments the helix was excited first. Whatever might be the direction of the current through the helix, the bar always set its length perpendicular to the axis of the latter, and parallel to the coils.

When the direction of the helix current, and the polarity of the magnet, were those shown in fig. 21, the deflection was to the dotted position.

Interrupting all, and reversing the current in the helix; on exciting the magnet the deflection was that shown in fig. 22.

Changing the polarity of the magnet, and preserving the helix current in its former direction, the deflection was that shown in fig. 23.

Interrupting all, and reversing the current through the helix; when the magnetism was developed the deflection was that shown in fig. 24.

Abnormal Diamagnetic Bar.—This bar consisted of a prism of bismuth whose principal planes of crystallization were perpendicular to its length: the mode of experiment was the same as that applied in the other cases.

Acted upon by the magnet alone, the bar set its length from pole to pole: the magnetic excitation being that denoted by fig. 29, a current was sent through the helix in the direction of the arrow; the bar was deflected to the dotted position.

* Phil. Mag. vol. xxviii. p. 456.

Reversing the current through the helix, the deflection was that shown in fig. 30.

Interrupting both currents and reversing the magnetic poles; on sending a current through the helix as in the last experiment, the deflection was that shown in fig. 31.

Reversing the current through the helix, the deflection was that shown in fig. 32.

In the subsequent four experiments the helix was excited first.

Sending a current through the helix in the direction denoted by the arrow, the bar set its length at right angles to the convolutions, and parallel to the axis of the helix; when the magnetism was excited as in fig. 25, the deflection was to the dotted position.

When the current was sent through the helix in an opposite direction, the deflection was that shown in fig. 26.

Interrupting both currents, and reversing the poles of the magnet; on sending a current through the helix as in the last experiment, the deflection was that shown in fig. 27.

Reversing the current in the helix, the deflection was that shown in fig. 28.

In all these cases the position of equilibrium due to the first force was attained, before the second force was permitted to act.

It will be observed, on comparing the deportment of the normal paramagnetic bar with that of the normal diamagnetic one, that the position of equilibrium taken up by the latter, when operated on by the helix alone, is the same as that taken up by the former when acted on by the magnet alone: in both cases the position is from pole to pole of the magnet. A similar remark applies to the abnormal para- and diamagnetic bars. It will render the distinction between the deportment of both classes of bodies more evident, if the position of the two bars, before the application of the second force, be one and the same. When both the bars, acted on by one of the forces, are axial, or both equatorial, the contrast or coincidence, as the case may be, of the deflections from this common position by the second force will be more strikingly evident.

To effect the comparison in the manner here indicated, the figures have been collected together and arranged upon Plate I. The first column represents the deportment of the normal paramagnetic bar under all the conditions described; the second column, that of the normal diamagnetic bar; the third shows the deportment of the abnormal paramagnetic bar, and the fourth that of the abnormal diamagnetic bar.

A comparison of the first two columns shows us that the deportment of the normal magnetic bar is perfectly antithetical to that of the normal diamagnetic one. When, on the application of the second force, an end of the former is deflected to the right, the same end of the latter is deflected to the left. When the position of equilibrium of the magnetic bar, under the joint action of the two forces, is from N.E. to S.W., then the position of equilibrium for the diamagnetic bar is invariably from N.W. to S.E. There is no exception to this antithesis, and I have been thus careful to vary the conditions of experiment in all possible ways, on account of the divergent results

obtained by other inquirers. In his recent memoirs upon this subject, M. v. FEILITSCH states that he has found the deflection of diamagnetic bodies, under the circumstances here described, to be precisely the same as that of paramagnetic bodies: this result is of course opposed to mine; but when it is remembered that the learned German worked confessedly with the "roughest apparatus," and possessed no means of eliminating the effects of structure, there seems little difficulty in referring the discrepancy between us to its proper cause.

The same perfect antithesis will be observed in the case of the abnormal bars, on a comparison of the third and fourth columns. In all cases then, whether we apply the magnet singly, or the current singly, or the magnet and current combined, the deportment of the normal diamagnetic bar is opposed to that of the normal paramagnetic one, and the deportment of the abnormal paramagnetic bar is opposed to that of the abnormal diamagnetic one. But if we compare the normal paramagnetic with the abnormal diamagnetic bar, we see that the deportment of one is identical with that of the other*. The same identity of action is observed when the normal diamagnetic bar is compared with the abnormal paramagnetic one. The necessity of taking molecular structure into account in experiments of this nature could not, I think, be more strikingly exhibited.

For each of the bars, under the operation of the two forces, there is an oblique position of equilibrium: on the application of the second force, the bar swings like a pendulum beyond this position, oscillates round it, and finally comes to rest there. Hence, if before the application of the second force the bar occupy the axial position, the deflection, when the second force is applied, appears to be from the axis to the equator; but if it first occupy the equatorial position, the deflection appears to be from the equator to the axis.

We have already shown that the repulsion of diamagnetic bodies is to be referred to a state of excitement induced by the magnet which acts upon them: it has been long known that the attraction of paramagnetic bodies is due to the same cause. The experiments just described exhibit to us bars of both classes of bodies moving in the magnetic field: such motions occur in virtue of the induced state of the body, and the relation of that state to the forces which act upon the mass. We have seen that in all cases the antithesis between both classes of bodies is maintained. Whatever therefore the state of the paramagnetic bar, under magnetic excitement, may be, a precisely antithetical state would produce all the phenomena of the diamagnetic bar. If the bar of iron be polar, a reverse polarity on the part of bismuth would

* Identical to the eye, but not to the mind. The notion appears to be entertained by some, that, by changing molecular structure, I had actually converted paramagnetic substances into diamagnetic ones, and *vice versâ*. No such change, however, can cause *the mass* of a diamagnetic body suspended by its centre of gravity to be *attracted*, or the mass of a paramagnetic body to be *repelled*. But by a change of molecular structure one of the forces may be so caused to apply itself that it shall present to the eye all the *directive* phenomena exhibited by the other.—J. T., May 5, 1855.

produce the effects observed. From this point of view all the movements of diamagnetic bodies become perfectly intelligible, and the experiments to be recorded in the next chapter are not calculated to diminish the probability of the conclusion that diamagnetic bodies possess a polarity opposed to that of magnetic ones.

The phenomena to which we have thus far referred consist in the rotations of elongated bars about their axes of suspension. The same antithesis, however, presents itself when we compare the *motion of translation* of a paramagnetic body, within the coil, with that of a diamagnetic one. A paramagnetic sphere was attached to the end of a horizontal beam and introduced into the coil: the magnet being excited the sphere could be made to traverse the space within the coil in various directions, by properly varying the current through the coil. A diamagnetic sphere was submitted to the same examination, and it was found that the motions of both spheres, when operated on by the same forces, were always in opposite directions.

V. FURTHER COMPARISON OF PARAMAGNETIC AND DIAMAGNETIC PHENOMENA:— DIAMAGNETIC POLARITY.

When an iron bar is placed within a helix, it is well known that on sending a current through the latter the bar is converted into a magnet, one end of the bar thus excited being attracted, and the other end repelled by the same magnetic pole. In this *twoness* of action consists what is called the *polarity* of the bar: we will now consider whether a bar of bismuth exhibits similar effects.

Fig. 39 Plate II. represents the disposition of the apparatus used in the examination of this question. AB is a helix of covered copper wire one-fifteenth of an inch in thickness: the length of the helix is 5 inches, external diameter 5 inches, and internal diameter 1·5 inch. Within this helix a bar of bismuth $6\frac{1}{2}$ inches long and 0·4 of an inch thick was suspended. The suspension was effected by means of a light beam, from two points of which, sufficiently distant from each other, depended two silver wires each ending in a loop: into these loops, ll', the bar of bismuth was introduced, and the whole was suspended by a number of fibres of unspun silk from a suitable point of support. Fig. 39 a is a side view of the arrangement used for the suspension of the bar. Before introducing the latter within the helix, it was first suspended in a receiver, which protected it from air currents, and in which it remained until the torsion of the fibre had exhausted itself: the bar was then removed, and the beam, without permitting the fibre to twist again, was placed over the helix so as to receive the bar introduced through the latter. From the ends of this helix two wires passed to a current reverser R, from which they proceeded further to the poles of a voltaic battery. CD and EF are two electro-magnetic spirals, each 12 inches long, $5\frac{1}{2}$ inches external and 2 inches internal diameter. The wire composing them is one-tenth of an inch thick, and so coiled that the current could be sent through four wires simultaneously. Within these spirals were introduced two cores of soft iron 2 inches thick and 14 inches long: the ends of the cores appear at P and P′. The spirals were so

connected together that the same current excited both, thus developing the same magnetic strength in the poles P P′. From the ends of the spirals proceeded wires to the current reverser R′, and thence to a second battery of considerably less power than the former. By means of the reverser R′ the polarity of the cores could be changed; P′ could be converted from a south pole to a north pole, at the same time that P was converted from a north pole to a south pole. Lastly, by a change of the connexions between the two spirals, the cores could be so excited as to make the poles of the same quality, both north or both south.

The diameter of the cylindrical space, within which the bismuth bar was suspended, was such as to permit of a free play of the ends of the bar through the space of an inch and a half. Having seen that the bar swung without impediment, and that its axis coincided as nearly as possible with the axis of the helix, a current from the battery was sent through the latter. The magnetism of the cores P and P′ was then excited, and the action upon the bismuth bar observed. M. v. Feilitsch has attempted a similar experiment to that here described, but without success: when, however, sufficient power is combined with sufficient delicacy, the success is complete, and the most perfect mastery is obtained over the motions of the bar.

The helix above described is the one which I have found most convenient for the experiments; various other helices, however, were tried with a result equally certain, if less energetic. The one first made use of was 4 inches long, 3 inches exterior diameter and three-quarters of an inch interior diameter, with wire one-fifteenth of an inch in thickness, the bar being suspended by a fibre which passed through a slit in the helix: sending through this helix a current from a battery of 10 cells, and exciting the cores by a current from 1 cell, the phenomena of repulsion and *attraction* were exhibited with all desirable precision.

I shall now proceed to describe the results obtained by operating in the manner described. The bismuth bar being suitably suspended, a current was sent through the helix, so that the direction of the current *in the upper half* was that indicated by the arrow in fig. 40. On exciting the magnet, so that the pole N was a north pole and the pole S a south pole, the ends of the bar of bismuth were *repelled*. The final position of the bar was against the side of the helix most remote from the magnets: it is shown by dots in the figure.

By means of the reverser R the current was now sent through the helix in the direction shown in fig. 41: the bar promptly left its position, crossed the space in which it could freely move, and came to rest as near the magnets as the side of the helix would permit it. *It was manifestly attracted by the magnets.*

Permitting the current in the helix to flow in the last direction, the polarity of the cores of soft iron was reversed: we had then the state of things sketched in fig. 42; the bismuth bar instantly loosed from the position it formerly occupied, receded from the magnet and took up finally the position marked by the dots.

After this new position had been attained, the current through the helix was re-

versed: the bar promptly sailed across the field towards the magnets, and finally came to rest in the dotted position, fig. 43. In all these cases, when the bar was freely moving in any direction, under the operation of the forces acting upon it, the reversion either of the current in the helix or of the polarity of the cores arrested the motion; approach was converted into recession and recession into approach.

The ends of the helix in these experiments were not far from the ends of the soft iron cores; and it might therefore be supposed that the action was due to some modification of the cores by the helix, or of the helix by the cores. It is manifest that the magnets can have no *permanent* effect upon the helix; the current through the latter, measured by a tangent galvanometer, is just as strong when the cores are excited as when they are unexcited. The helix may certainly have an effect upon the cores, and this effect is either to enfeeble the magnetism of the cores or to strengthen it; but if the former, and the bar were the simple bismuth which it is when no current operates on it, the action, though weakened, *would still be repulsive*, and if the latter, the increase would simply augment the repulsion. The fact, however, of the ends of the bar being *attracted*, proves that the bar has been thrown into a peculiar condition by the current circulating in the surrounding coil. Changing the direction of the current in the coil, we find that the self-same magnetic forces which were formerly attractive are now repulsive; to produce this effect the condition of the bar must have changed with the change of the current; or, in other words, the bar is capable of accepting *two different states* of excitement, which depend upon the direction of the current.

In order, however, to reduce as far as possible the action of the helix upon the cores, I repeated the experiments with the small helix referred to in fig. 6, page 25. It will be remembered that this helix is but an inch in length, and that the bismuth bar is $6\frac{1}{2}$ inches long. I removed the magnets further apart, so that the centres of the cores were half an inch beyond the ends of the bismuth bar, while the helix encircled only an inch of its central portion: in this position, when the helix was excited, there was no appreciable magnetism excited by it in the dormant cores; at least, if such were excited, it was unable to attract the smallest soft iron nail. Here then we had cores and helix sensibly independent of each other, but the phenomena appeared as before. The bar could be held by the cores against the side of the helix, with its ends only a quarter of an inch distant from the ends of the cores; on reversing either current the ends instantly receded, but the recession could be stopped by again changing the direction of the current. With a tranquil atmosphere, and an arrangement for reversing the current without shock or motion, the bar obeyed in an admirable manner the will of the experimenter, and, under the operation of the same forces, exhibited all the deflections sketched in figs. 40, 41, 42 and 43.

The motion of the bar cannot be referred to the action of induced currents. The bar was brought into the centre of the hollow cylinder in which it swung and held there; the forces were all in action, and therefore all phenomena of induction passed; the arrangement of the forces being that shown in fig. 40, on releasing the bar it was

driven from the cores, whereas when the arrangement was that shown in fig. 41, it was drawn towards them.

But it does not sufficiently express the facts to say that the bar is capable of two different states of excitement; it must be added, that both states exist simultaneously in the excited bar. We have already proved that the state necessary for the action of one pole is not that which enables an opposite pole to produce the same action; hence, when the two ends of the bar are attracted or repelled, at the same time, by two opposite poles, it is a proof that these two ends are in different states. But if this be correct, we can test our conclusion by reversing one of the poles; the direction of its force being thereby changed, it ought to hold the other pole in check and prevent all motion in the bar. This is the case: if, in any one of the instances cited, the polarity of either of the cores be altered; if the south be converted into a north, or the north into a south pole, thus making both poles of the same quality, the repulsion of the one is so nearly balanced by the attraction of the other, that the bar remains without motion towards either of them.

To carry the argument a step further, let us fix our attention for an instant upon fig. 40. The end of the bar nearest to the reader is repelled by a south pole; the same end ought to be *attracted* by a north pole. In like manner, the end of the bar most distant from the reader is repelled by a north pole, and hence the state of that end ought to fit it for *attraction* by a south pole. If, therefore, our reasoning be correct, when we place a north pole opposite to the lower end of the bar, and on the same side of it as the upper north pole, and a south pole opposite the upper end of the bar and on the same side of it as the lower south pole, the simultaneous action of these four poles ought to be more prompt and energetic than when only two poles are used. This arrangement is shown in Plate III.: the two poles to the right of the bismuth bar must be of the same name, and the two to the left of the bar of the opposite quality. If those to the right be both north, those to the left must be both south, and *vice versâ*. The current reverser for the magnets appears in front, that for the helix is hidden by the figure. The above conclusion is perfectly verified by experiments with this apparatus, and the twofold deflection of the bismuth bar is exhibited with remarkable energy*.

The bar used in these cases is far heavier than those commonly made use of in experiments on diamagnetism; but the dimensions stated do not mark the practical limit of the size of the bar. A solid bismuth cylinder, 14 inches long and 1 inch in diameter, was suspended in a helix 5·7 inches long, 1·8 inch internal diameter, 4 inches external diameter, and composed of copper wire 0·1 of an inch in thickness: when a current of twenty cells was sent through the helix, and the magnets (only

* These experiments, and almost all the others mentioned in this memoir, may be exhibited in the lecture room. By attaching indexes of wood to the bars of bismuth, and protecting the indexes from air currents by glass shades, the motions may be made visible to several hundreds at once. See a description of a Polymagnet, Phil. Mag. June 1855.—J. T.

two of them were used) were excited by one cell, all the phenomena exhibited by figs. 40, 41, 42 and 43, were distinctly exhibited.

A considerable difference is always necessary between the strength of the current passing through the helix and that which excites the cores, so as to prevent the induction of the cores, which, of itself, would be followed by repulsion, from neutralizing, or perhaps inverting, the induction of the helix. When *two* magnets were used and the helix was excited by ten cells, I found the magnetic excitement by one or two cells to be most advantageous; when the cores were excited by ten, or even five cells, the action was always repulsive*. When four magnets were applied and the helix was excited by a battery of ten or fifteen cells, a power of five cells for the magnets was found efficient.

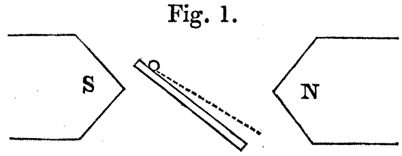
The deportment of paramagnetic bodies is so well known that it might be left to the reader to discern that in all the cases described it is perfectly antithetical to that of the diamagnetic body. I have nevertheless thought it worth while to make the corresponding experiments with an iron bar; to facilitate comparison the results are placed side by side in Plate II. with those obtained with the bar of bismuth. It must be left to the reader to decide whether throughout this inquiry the path of strict inductive reasoning has been adhered to: if this be the case, then the inference appears unavoidable, *that the diamagnetic force is a polar force, the polarity of diamagnetic bodies being opposed to that of paramagnetic ones under the same conditions of excitement*†.

* The perfect similarity of this deportment to that of soft iron under the same circumstances is evident.

† I would gladly refer to M. PLÜCKER's results in connexion with this subject had I been successful in obtaining them; I will here however introduce the description of his most decisive experiment in his own words. (See Scien. Mem. New Ser. p. 336.)

"From considerations of which we shall speak afterwards, it appeared to me probable that bismuth not only assumes polarity in the vicinity of a magnetic pole, but that it also retains the polarity for some time after the excitation has taken place; or, in other words, that bismuth retains a portion of its magnetism permanently, as steel, unlike soft iron, retains a portion of the magnetism excited in it by induction. My conjecture has been corroborated by experiment.

Fig. 1.



"I hung a bar of bismuth, 15 millims. long and 5 millims. thick, between the pointed poles of the large electro-magnet; it was suspended horizontally from a double cocoon-thread, fig. 1. The distance between the points was diminished until the bar could barely swing freely between them. A little rod of glass was brought near to one of the points, so that the bismuth bar, before the magnetism was excited, and in consequence of the torsion, leaned against the glass rod. On exciting the magnet by a current of three of GROVE's elements, the bismuth, prevented from assuming the equatorial position, pressed more forcibly against the glass rod; when the current was interrupted, the bar remained still in contact with the rod, while its free end vibrated round its position of equilibrium. The current was closed anew and then reversed by a gyrotrope. In consequence of this reversion, the bar of bismuth, loosening from the glass rod, moved towards the axial position, but soon turned and pressed against the glass as before, or in some cases having passed quite through the axial position was driven round with the reversed ends into the equatorial....This experiment, which was made with some care, proves that the bismuth requires time to reverse its polarity."

I have repeated this experiment with great care, and have obtained in part the effect described: it is perfectly

VI. CONCLUDING OBSERVATIONS: ON M. WEBER'S THEORY OF DIAMAGNETIC POLARITY*, AND ON AMPÈRE'S THEORY OF MOLECULAR CURRENTS.

It is well known that a voltaic current exerts an attractive force upon a second current, flowing in the same direction; and that when the directions are opposed to each other the force exerted is a repulsive one. By coiling wires into spirals, AMPÈRE was enabled to make them produce all the phenomena of attraction and repulsion exhibited by magnets, and from this it was but a step to his celebrated theory of molecular currents. He supposed the molecules of a magnetic body to be surrounded by such currents, which, however, in the natural state of the body mutually neutralized each other, on account of their confused grouping. The act of magnetization he supposed to consist in setting these molecular currents parallel to each other, and starting from this principle he reduced all the phenomena of magnetism to the mutual action of electric currents.

If we reflect upon the experiments recorded in the foregoing pages from first to last; on the inversion of magnecrystallic phenomena by the substitution of a magnetic constituent for a diamagnetic; on the analogy of the effects produced in magnetic and diamagnetic bodies by compression; on the antithesis of the rotating actions described near the commencement; on the indubitable fact that diamagnetic bodies, like magnetic ones, owe their phenomena to an induced condition into which they are thrown by the influencing magnet, and the intensity of which is a function of the magnetic strength; on the circumstance that this excitation, like that of soft iron, is of a dual character; on the numerous additional experiments which have been recorded, all tending to show the perfect antithesis between the two classes of bodies;—we can hardly fail to be convinced that Mr. FARADAY's first hypothesis of diamagnetic action is the true one—that diamagnetic bodies operated on by magnetic forces possess a polarity "the same in kind as, but the reverse in direction of that acquired by magnetic bodies." But if this be the case, how are we to conceive of the *physical mechanism* of this polarity? According to COULOMB's and POISSON's theory, the act of magnetization consists in the decomposition of a neutral magnetic fluid; the north pole of a magnet, for example, possesses an attraction for the south fluid of a piece of soft iron submitted to its influence, draws the said fluid towards it, and with it the material particles with which the fluid is associated. To account

easy to produce the rotation of the bar. The cause of this rotation, however, was in my case as follows:—When the magnet was unexcited the position of equilibrium of the axis of the bar acted upon by the torsion of the fibre, was that shown by the dotted line in the figure; when the magnetism was developed, the repulsive force acting on the free end of the bar necessarily pushed it beyond the dotted line—an action which was perfectly evident when the attention was directed towards it. On reversing the current, a little time was required to change the polarity of the iron masses; during this time the free end of the bismuth *fell* towards its former position, and the velocity acquired was sufficient to carry it quite beyond the pole points. The only difference between M. PLÜCKER and myself is, that I obtained the same result by simply *intercepting* the current as by reversing it. I may remark that I have submitted ordinary bismuth to the most powerful and delicate tests, but as yet I have never been able to detect in it a trace of that retentive power ascribed to it by M. PLÜCKER.

* POGG. Ann. vol. lxxxvii. p. 145, and TAYLOR's Scien. Mem. New Ser. p. 163.

for diamagnetic phenomena this theory seems to fail altogether: according to it indeed the oft-used phrase, 'a north pole exciting a north pole, and a south pole a south pole,' involves a contradiction. For if the north fluid be supposed to be *attracted* towards the influencing north pole, it is absurd to suppose that its presence there could produce *repulsion.* The theory of AMPÈRE is equally at a loss to explain diamagnetic action; for, if we suppose the particles of bismuth surrounded by molecular currents, then according to all that is known of electro-dynamic laws, these currents would set themselves parallel to, and in the same direction as those of the magnet, and hence attraction, and not repulsion, would be the result. The fact, however, of this not being the case proves that these molecular currents are not the mechanism by which diamagnetic induction is effected. The consciousness of this, I doubt not, drove M. WEBER to the assumption that the phenomena of diamagnetism are produced by molecular currents, not *directed,* but actually *excited* in the bismuth by the magnet. Such induced currents would, according to known laws, have a direction *opposed* to those of the inducing magnet, and hence would produce the phenomena of repulsion. To carry out the assumption here made, M. WEBER is obliged to suppose that the molecules of diamagnetic bodies are surrounded by channels, in which the induced molecular currents, once excited, continue to flow without resistance.

This theory, notwithstanding its great beauty, is so extremely artificial, that I imagine the general conviction of its truth cannot be very strong; but there is one conclusion flowing from it which appears to me to be in direct opposition to experimental facts. The conclusion is, "*that the magnetism of two iron particles in the line of magnetization is increased by their reciprocal action; but that, on the contrary, the diamagnetism of two bismuth particles lying in this direction is diminished by their reciprocal action.*" The reciprocal action of the particles varies inversely as the cube of the distance between them: at a distance expressed by the number 1, for example, the enfeeblement is eight times what it would be at the distance 2.

The conclusion, as regards the iron, is undoubtedly correct; but I believe experiment proves that the mutual action of diamagnetic molecules, when caused to approach each other, *increases* their repulsive action. I have had massive iron moulds made and coated with copper by the voltaic current; into these fine bismuth powder has been introduced and submitted to powerful hydraulic pressure. No sensible fact can, I think, be more certain, than that the particles of this dust are brought into closer proximity along the line in which the pressure is exerted, and this is the line of *strongest diamagnetization.* If a portion of the compressed mass be placed upon the end of a torsion beam and the amount of repulsion measured, it will be found that the repulsion is a maximum when the line of magnetization coincides with the line of compression; or, in other words, with that line in which the particles are packed most closely together: if the bismuth were fixed, and the magnet moveable, the former would repel the latter with a maximum force with the line of compression parallel to the direction of magnetization: it is a stronger *diamagnet* in this direction

than in any other. Cubes of bismuth, which, in virtue of their crystallization, possessed a line of minimum magnetization, have been placed in those moulds and pressed closely together in the direction of the said line: the approximation of the particles thus effected has converted the direction spoken of from one of minimum into one of maximum magnetization. It would be difficult for me to say how many diamagnetic bodies I have submitted to compression, some massive, some in a state of powder, but in no single instance have I discovered an exception to the law that the line of compression of purely diamagnetic bodies is the line of strongest diamagnetization. The approximation of diamagnetic particles is therefore accompanied by an augmentation of their power, instead of a diminution of it, as supposed by the theory of M. WEBER.

Any hypothesis which involves the idea of the diminution of the diamagnetic action of a body by the approximation of its particles, is, I believe, opposed to facts. Such a hypothesis must, I imagine, form the basis of the following remark of Professor W. THOMSON:—referring to "a thin bar or needle of a diamagnetic substance," he says, "such a needle has no tendency to arrange itself across the lines of magnetic force; but, as will be shown in a future paper, if it be very small compared with the dimensions and distance of the magnet, the direction it will assume, when allowed to turn freely round its centre of gravity, will be that of the lines of force*." I have not found in any of the subsequent numbers of the Philosophical Magazine the proof here promised†. But I doubt not the conclusion involves the assumption that the mutual action of diamagnetic particles is to weaken each other, and hence to produce a more feeble magnetization *along* a thin diamagnetic bar than *across* it—an assumption which, as already shown, is contradicted by experiment.

It is scarcely possible to reflect upon the discovery of FARADAY in all its bearings, without being deeply impressed with the feeling that we know absolutely nothing of the physical causes of magnetic action. We find the magnetic force producing, by processes which are evidently similar, two great classes of effects. We have a certain number of bodies which are attracted by the magnet, and a far greater number which are repelled by the same agent. Supposing these facts to have been known to AMPÈRE, would he have satisfied his profound mind by founding a theory which accounts for only the smaller portion of them? This theory is admirable as far as it goes, but the generalization is yet to come which shall show the true relationship of phenomena, towards whose connexion the theory of AMPÈRE furnishes at present no apparent clue.

Royal Institution, October 1854.

* Philosophical Magazine, vol. xxxvii. p. 244.

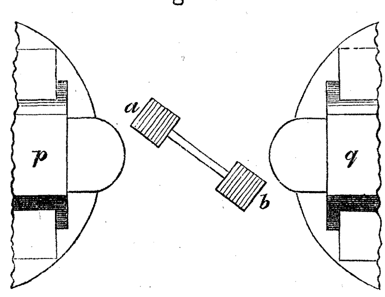
† This remark appears to have induced Mr. THOMSON to publish the proof referred to in the last Number of the Philosophical Magazine. The arguments there brought forward have been long familiar to me, but I regret to say that I cannot attach much real value to them. At some future day I hope to be able to justify the scepticism which I here venture to express.—J. T., May 5, 1855.

NOTE *on* M. MATTEUCCI'S *objections.*

The foregoing memoir was on the point of leaving my hands for the Royal Society, when accident, backed by the kindness of Mr. FARADAY, placed the '*Cours Spécial*' of M. MATTEUCCI, recently published in Paris, in my hands. An evening's perusal of this valuable work induces me to append the following remarks to the present paper.

M. MATTEUCCI honours the researches which bear my name, and those which I published in connexion with M. KNOBLAUCH, with a considerable share of his attention. He corroborates all the experimental facts, but at the conclusion states three objections to the manner in which these facts have been explained. "La faveur," writes the learned Italian, "avec laquelle les idées de MM. TYNDALL et KNOBLAUCH ont été accueillies m'imposent le devoir de ne pas vous laisser ignorer les objections qui s'élèvent contre elles. La première consiste dans la différence très-grande et constant dans la force qui fait osciller entre les poles un aiguille de bismuth cristallisé, suivant que ses clivages parallèles à sa longueur sont suspendus verticalement ou dans un plan horizontal: c'est différence me parait inconciliable avec le résultat déjà rapporté de l'expérience de M. TYNDALL, sur lequel se fonde l'explication des phénomènes magneto-cristallisés. Mais une objection encore plus grave est celle du mouvement d'*attraction** vers les poles qui se manifeste dans les prismes de bismuth cristallisé dont les clivages sont perpendiculaires à leur longueur. Pour rendre la conséquence de cette dernière expérience encore plus évidente, j'ai fixé deux cubes de bismuth, qui ont deux faces opposées naturelles et parallèles aux plans de clivage, aux extrémités d'un petit levier de verre, ou de sulphate de chaux, suspendu par un fil de cocon au milieu de champ magnétique entre les extrémités polaires d'un electro-aimant (fig. 27); lorsque les deux cubes ont les clivages verticaux et perpendiculaires à la longueur à l'aiguille, au moment où le circuit est fermé, l'aiguille est attiré, *quelle que soit la position* qu'elle occupe dans le champ magnétique, et se fixe en equilibre dans la ligne polaire.....Il me semble impossible d'expliquer ces mouvements du bismuth cristallisé, comme on a essayé de le faire, à la force repulsive de l'aimant, qui, suivant l'expérience de M. TYNDALL†, s'exerce avec plus d'intensité parallèlement aux clivages que dans la direction perpendiculaire à ces plans.

Fig. 27*a*.



"Remarquons encore qu'on ne trouve pas constamment l'accord qui devrait exister, selon les idées de MM. TYNDALL et KNOBLAUCH, entre les phénomènes magneto-cristallisés et les effets produits par la compression dans le bismuth, si l'on considère ces plans de clivages et la ligne suivant laquelle la compression a eu lieu comme jouissant des même propriétés‡."

With regard to the first objection, I may say that it is extremely difficult to meet

* This is in reality not a 'movement of *attraction*,'—see Appendix to the present paper.—J. T. May 1855.

† This was first proved by Mr. FARADAY.—J. T.

‡ Cours Spécial sur l'Induction, &c., p. 255.

one so put; it is simply an opinion, and I can scarcely say more than that mine does not coincide with it. I would gladly enter upon the subject and endeavour to give the objection a scientific form were the necessary time at my disposal, but this, I regret to say, is not the case at present. I shall moreover be better pleased to deal with the objection after it has assumed a more definite form in the hands of its proposer, for I entertain no doubt that it is capable of a sufficient answer. The second objection M. MATTEUCCI considers to be a more grave one. The facts are as follows:—the repulsion of a mass of crystallized bismuth depends upon the direction in which the mass is magnetized. When the magnetizing force acts in a certain direction, the intensity of magnetization, and the consequent repulsion of the mass, is a maximum. This is proved by placing the mass upon the end of a torsion beam and bringing its several directions successively into the line of the magnetic force. POISSON would have called such a direction through the mass a principal axis of magnetic induction, and I have elsewhere called it a line of elective polarity. When a sphere or cube of bismuth is freely suspended in the magnetic field, with the direction referred to horizontal, in all positions except two the forces acting on the mass tend to turn it; those positions are, when the line of maximum magnetization is axial and when it is equatorial, the former being a position of unstable, and the latter a position of stable equilibrium. When the above line is oblique to the direction magnetization, the sphere or cube will turn round its axis of suspension until the direction referred to has set itself at right angles to the line joining the poles. Now if the direction of maximum magnetization be transverse to an elongated mass of bismuth, such a mass must, when the said direction recedes to the equator, set its length from pole to pole. The facts observed by M. MATTEUCCI seem to me to be a simple corroboration of this deduction*.

The third objection is directed against an imaginary case, "si l'on considère les plans de clivage et la ligne de compression comme jouissant les même propriétés." It must be evident that a crystal like bismuth, possessing a number of cleavages of unequal values, cannot be compared in all respects with a body which has suffered pressure *in one direction* only. I have no doubt whatever that by a proper application of force, in different directions, a compressed mass might be caused to imitate to perfection every one of the actions exhibited by crystallized bismuth. Indeed I would go farther, and say, that I shall be happy to undertake to reproduce, with bismuth powder, the deportment of any diamagnetic crystal whatever that M. MATTEUCCI may think proper to name.

In looking further over M. MATTEUCCI's instructive book, I find another point alluded to in a manner which tempts me to make a few remarks in anticipation of a fuller examination of the subject. The point refers to the reciprocal action of the particles of magnetic and diamagnetic bodies. It is easy to see, that if the attraction of a bar of iron varies simply as the number of the particles attracted, then, inasmuch as the weight of the body varies in the same ratio, and the moment of inertia

* For a more complete examination of this subject see the "Appendix" to this paper.—J. T., May 1855.

as the weight, the times of oscillation of two masses of the same length, but possessing different numbers of attracting particles, must be the same. COULOMB indeed mixed iron filings with wax, so as to remove the particles out of the sphere of their mutual inductive action, and proved that when needles of equal lengths, but of different diameters, were formed from the same mixture, the duration of an oscillation was the same for all. From this he inferred that the attractive force is simply proportional to the number of ferruginous particles; but this could not be the case if these particles exerted any sensible reciprocal action, either tending to augment or diminish the induction due to the direct action of the magnet. On account of such a mutual action, two bars of soft iron, of the same length, and of different diameters, have not the same time of oscillation.

In examining the question whether the particles of diamagnetic bodies exert a similar reciprocal action, M. MATTEUCCI fills quills of the same length, and of different diameters, with powdered bismuth, and finds that there is no difference between the duration of an oscillation of the thick ones and the slender ones; from this he infers that there can be no reciprocal action among the particles of the bismuth.

Now it is not to be imagined that even in COULOMB's experiments with the iron filings the molecular induction was absolutely nothing, but simply that it was so enfeebled by the separation of the particles that it was insensible in the experiments. This remark applies with still greater force to M. MATTEUCCI's experiments with the bismuth powder; for the enfeeblement of a force already so weak, by the division of the diamagnetic mass into powder, must of course practically extinguish all reciprocal action of the particles, even supposing a weak action of the kind to exist when the mass is compact.

I will not here refer to my own experiments on compressed bismuth, but will take a result arrived at by M. MATTEUCCI himself while repeating and corroborating these experiments. "I made," says M. MATTEUCCI, "two cylinders of bismuth precisely of the same dimensions, the one compressed, the other in its natural state, and found that the compressed mass had a diamagnetic power *distinctly superior* to that of natural bismuth*." Now M. MATTEUCCI, in his 'Cours Spécial,' has made his own choice of a test of reciprocal molecular action; he assumes that if cylinders of the same length, but of different masses, have equal times of oscillation, it is a conclusive proof that there is no action of the kind referred to. This necessarily implies the assumption, that were the times of oscillation *different*, a reciprocal action would be demonstrated. Now, according to his experiments described in the Association Report, the times of oscillation *are* different; the diamagnetism of the compressed cylinder is "*distinctly superior*" to that of the uncompressed one: *the diamagnetic effect increases in a greater proportion than the quantity of matter*; and hence, on M. MATTEUCCI's own principles, the result negatived by his experiments on powdered bismuth is fairly established by those which he has made with the compressed substance.

* Report of British Association for 1852, Transactions of Sections, p. 7.

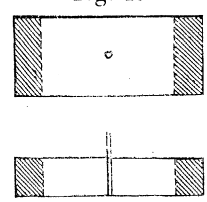
APPENDIX.

Received December 21, 1854.

Reflecting further on the subject of diamagnetic polarity, an experiment occurred to me which constitutes a kind of crucial test to which the conclusions arrived at in the foregoing memoir may be submitted.

Two square prisms of bismuth, 0·43 of an inch long and 0·2 of an inch wide, were laid across the ends of a thin plate of cedar wood, and fastened there by white wax. Another similar plate of wood was laid over the prisms, and also attached to them by wax; a kind of rectangular box was thus formed, one inch long and of the same width as the length of the prisms, the ends of the box being formed by the prisms, while its sides were open. Both plates of wood were pierced through at the centre, and in the aperture thus formed a wooden pin was fixed, which could readily be attached to a suspending fibre. Fig. 1 represents the arrangement both in plan and section.

Fig. 1.



The prisms first chosen were produced by the compression of fine bismuth powder, without the admixture of gum or any other foreign ingredient, the compressed mass being perfectly compact and presenting a surface of metallic brilliancy. If such a mass be placed on the end of a torsion balance and a magnetic pole is brought to bear upon it, I have proved the repulsion to be maximum when the direction in which the mass has been compressed is in the continuation of the axis of the magnet. A comparative view of the repulsion in this direction, and in another perpendicular to it, is given in the following Table.

Compressed bismuth powder.

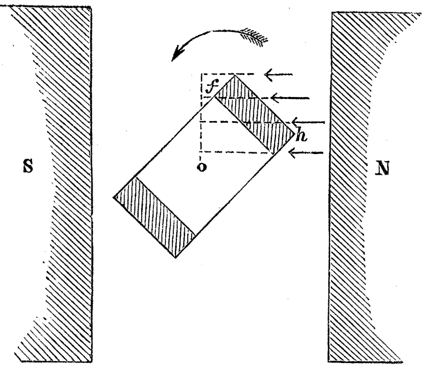
Strength of magnet.	Repulsion. line of pressure axial.	Repulsion. line of pressure equatorial.
5·8	22	13
8·4	46	31
10·0	67	46
11·9	98	67

We see here that the repulsion, when the line of pressure is axial, exceeds what occurs when the same line is equatorial by fully one-half the amount of the latter. Now this can only be due to the more intense magnetization, or rather diamagnetization, of the bismuth along the line of pressure; and in the experiment now to be described I availed myself of this fact to render the effect more decided.

The prisms of bismuth were so constructed that the line of pressure was parallel to the length of each. The rectangular box before referred to was suspended from

its centre of gravity O in the magnetic field, so that the two prisms were in the same horizontal plane. Let the position of the box thus suspended horizontally be that shown in fig. 2. For the sake of simplicity, we will confine our attention to the action of one of the poles N, which may be either flat or rounded, upon the prism *hf* adjacent to it, as indeed all the phenomena to be described can be produced before a single pole. The direction of the force emanating from N is represented by the arrows, and if this force be *purely repulsive*, the action upon every single particle of the diamagnetic mass furnishes a moment which, in the position here assumed, tends to turn the rectangular box in the direction marked by the arrow. It is perfectly impossible that such a system of forces could cause the box to turn in a direction opposed to the arrow; yet this is the precise direction in which the box turns when the magnetic force is developed.

Fig. 2.



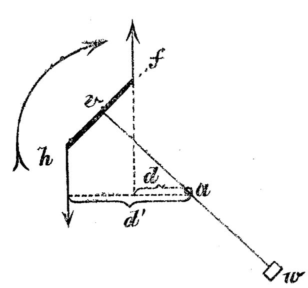
Here, then, we have a mechanical effect which is perfectly inexplicable on the supposition that the diamagnetic force is purely repulsive. But if the conclusions arrived at in the foregoing memoir be correct, if the diamagnetic force be a polar force, then we must assume that attraction and repulsion are developed simultaneously, as in the case of ordinary magnetic phenomena. Let us examine how this assumption will affect the analysis of the experiment before us.

The marked end of a magnetic needle is pulled towards the north magnetic pole of the earth; and yet, if the needle be caused to float upon a liquid, there is no motion of its mass towards the terrestrial pole referred to. The reason of this is known to be, that the south end of the needle is repelled by a force equal to that by which the north, or marked end, is attracted. These two equal and opposite forces destroy each other as regards *a motion of translation*, but they are effective in producing *a motion of rotation*. The magnetic needle, indeed, when in a position oblique to the plane of the magnetic meridian, is solicited towards that plane by a mechanical couple, and if free to move will turn and find its position of equilibrium there.

Let such a needle, *fh*, be attached, as in fig. 3, to the end of a light wooden beam, *vw*; let the beam and needle be suspended horizontally from the point *a*, round which the whole system is free to turn, the weight of the needle being balanced by a suitable counterpoise, *w*; let the north pole of the earth be towards N. Supposing the beam to occupy a position oblique to the magnetic meridian, as in the figure, the end *f*, or the marked end, of the needle is solicited towards N by a force ϕ, and the tendency of this force to produce rotation in the direction of the arrow is expressed by the

Fig. 3.

N



product of φ into the perpendicular drawn from the axis of rotation upon the direction of the force. Setting this distance $=d$, we have the moment of φ in the direction stated,

$$=\varphi d.$$

The end h of the needle is repelled by the earth's magnetic pole with a force φ': calling the distance of the direction of this latter force from the axis of rotation d', we have the moment of φ' in a direction opposed to the arrow,

$$=\varphi' d'.$$

Now as the length of the needle may be considered a vanishing quantity, as compared with its distance from the terrestrial pole, we have practically

$$\varphi=\varphi',$$

and consequently

$$\varphi d<\varphi' d'.$$

The tendency to turn the lever in a direction opposed to the arrow is therefore predominant; the lever will obey this tendency and move until the needle finds itself in the magnetic meridian: when this position is attained, the predominance spoken of evidently ceases, and the system will be in equilibrium. Experiment perfectly corroborates this theoretic deduction.

In this case, the centre of gravity of the needle recedes from the north magnetic pole as if it were repelled by the latter; but it is evident that the recession is not due either to the attraction or repulsion of the needle considered as a whole, but simply to the mechanical advantage possessed by the force φ', on account of its greater distance from the axis of rotation. If the force acting upon every particle of the needle were purely *attractive*, it is evident that no such recession could take place. Supposing, then, that we were simply acquainted with the fact, that the end f of the needle is attracted by the terrestrial pole, and that we were wholly ignorant of the action of the said pole upon the end h, the experiment here described would lead us infallibly to the conclusion that the end h must be repelled. For if it were attracted, or even if it were neither attracted nor repelled, the motion of the bar must be *towards* the pole N instead of in the opposite direction.

Let us apply this reasoning to the experiment with the bismuth prisms already described. The motion of the magnetic needle in the case referred to is not more inexplicable, on the assumption of a purely attractive force, than is the motion of our rectangular box on the assumption of a purely repulsive one; and if the above experiment would lead to the conclusion that the end h of the magnetic needle is repelled, the experiment with the bismuth leads equally to the conclusion that the end f of the prism hf, fig. 2, must be *attracted* by the pole N. The assumption of such an attraction, or in other words, of diamagnetic polarity, is alone capable of explaining the effect, and the explanation which it offers is perfect.

On the hypothesis of diamagnetic polarity, the prism hf turns a hostile end h to the magnetic pole N and a friendly pole f away from it. Let the repulsive force

acting upon the former be ϕ, and the attractive force acting upon the latter ϕ'. It is manifest that if ϕ were equal to ϕ', as in the case of the earth's action, or in other words, if the field of force were perfectly uniform, then, owing to the greater distance of ϕ' from the axis of rotation, from the moment at which the rectangular box quits the equatorial position, which is one of unstable equilibrium, to the moment when its position is axial, the box would be incessantly drawn towards the position last referred to.

But it will be retorted that the field of force is not uniform, and that the end h, on account of its greater proximity to the magnet, is more forcibly repelled than the end f is attracted: to this I would reply, that it is only in "fields" which are approximately uniform that the effects can be produced; but to produce motion towards the pole, it is not necessary that the field should be perfectly uniform: setting, as before, the distance of the direction of the force ϕ from the axis of rotation $=d$, and that of the force $\phi'=d'$, a motion towards the pole N will always occur whenever

$$\frac{d'}{d} > \frac{\phi}{\phi'}.$$

To ascertain the diminution of the force on receding from a polar surface such as that here used, I suspended a prism of bismuth, similar to those contained in the rectangular box, at a distance of 0·9 of an inch from the surface of the pole. Here, under the action of the magnet excited by a current of ten cells, the number of oscillations accomplished in a second was 17; at 0·7 of an inch distant the number was 18; at 0·5 of an inch distant the number was 19; at 0·3 distant the number was 19·5; and at 0·2 distant the number was 20. The forces at these respective distances being so very little different from each other, it follows that a very slight deviation of the box from the equatorial position is sufficient to give the moment of ϕ' a preponderance over that of ϕ, and consequently to produce the exact effect observed in the experiment.

The consistency of this reasoning is still further shown when we operate in a field of force which diminishes speedily in intensity as we recede from the magnet. Such a field is the space immediately in front of pointed poles. Suspending our rectangular box between the points, and causing the latter to approach until the box has barely room to swing between them, it is impossible to produce the phenomena which we have just described. The intensity with which the nearest points of the bismuth bar are repelled so much exceeds the attraction of the more distant end, that the moment of attraction is not able to cope successfully with the moment of repulsion; the bars are consequently repelled *en masse*, and the length of the box takes up a position at right angles to the line which unites the poles.

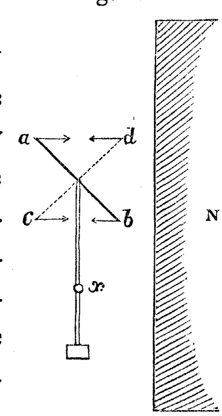
It is manifest, however, that by increasing the distance between the bismuth bar and the points acting upon it, we diminish the difference of action upon the two ends of the bar. When the distance is sufficient, we can produce, with the pointed poles, all the phenomena exhibited between flat or rounded ones.

All the effects which have been described are produced with great distinctness when, instead of compressed bismuth, two similar bars of the crystallized substance are used, in which the planes of principal cleavage are parallel to the length. Such bars are not difficult to procure, and they ought to hang in the magnetic field with the planes of cleavage vertical. It is unnecessary to describe the experiments made with such bars; they exhibit with promptness and decision all the effects observed with the compressed bismuth.

We have hitherto operated upon elongated masses of bismuth; but with the compressed substance, or with the substance crystallized uniformly in planes, as in the case last referred to, an elongation of the mass is not necessary to the production of the effects described. Previous, however, to the demonstration of this proposition, I shall introduce a kind of lemma, which will prepare the way for the complete proof.

Diamagnetic bodies, like paramagnetic ones, vary considerably in the intensity of their forces. Bismuth or antimony, for example, exhibits the diamagnetic force with greater energy than gold or silver, just as iron or nickel exhibits the magnetic force with greater energy than platinum or chromium. Let two thin bars, *ab*, *cd*, fig. 4, of two bodies of different diamagnetic powers, be placed at right angles to each other, so as to form a cross; let the cross be attached to the end of a lever and suspended horizontally from the point x, before the flat or rounded pole N of a magnet. Let the continuous line *ab* represent the needle of the powerful diamagnetic body, and the broken line *cd* that of the feeble one. On the former a mechanical couple acts in the direction denoted by the arrows at its ends; and on the latter a couple operates in the direction of the arrows at *its* ends. These two couples are evidently opposed to each other; but the former being, by hypothesis, the more powerful of the two, it will overcome the latter. The mechanical advantage possessed by the *attracted* end a of the more powerful bar, on account of its greater distance from the axis of suspension x, will, in an approximately uniform field of force which we here assume, cause the centre of gravity of the cross to move towards the pole N.

Fig. 4.



In the formation of such a cross, however, it is not necessary to resort to two different substances in order to find two needles of different diamagnetic powers; for in crystallized bodies, or in bodies subjected to mechanical pressure, the diamagnetic force acts with very different energies in different directions. Let a mass of a diamagnetic body which has been forcibly compressed in one direction be imagined; let two needles be taken from such a mass, the one with its length parallel, and the other with its length perpendicular to the line of pressure. Two such needles, though composed of the same chemical substance, will behave exactly as the two bars of the cross in the experiment last described; that needle whose length coincides with the line of pressure will bear the same relation to the other that the

needle of the powerfully diamagnetic substance bears to that of the feeble one. An inspection of the table at page 44 will show that this must be the case.

It is also shown in the following table, that in masses of crystallized bismuth the diamagnetic repulsion acts with very different energies in different directions. Cubes were taken from a mass of bismuth with the planes of principal cleavage parallel throughout to two opposite faces of each cube. The cubes were placed upon the ends of a torsion balance, and the diamagnetic repulsion was accurately measured when the force acted parallel to the planes of cleavage. The cubes were then turned 90° round, and the repulsion was measured when the force acted perpendicular to the planes referred to.

Cubes of crystallized bismuth.

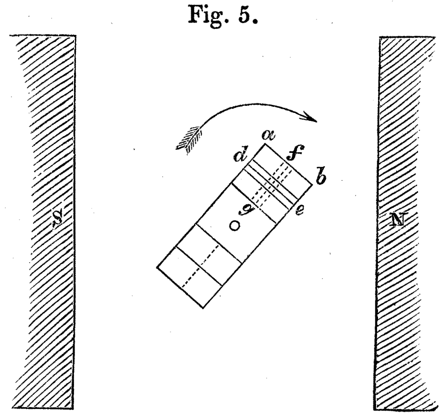
Strength of magnet.	Repulsion when the force was directed along the cleavage.	across the cleavage.
3·6	11·7	8
5·7	34·8	23
8·4	78	53
10·0	111	76·5
11·9	153	110

It is manifest from this table that bismuth behaves as a body of considerably superior diamagnetic power when the force acts *along* the planes of cleavage.

Let two indefinitely thin needles be taken from such a mass, the one with its length parallel, and the other with its length perpendicular to the planes of cleavage; it is evident that if two such needles be formed into a cross and subjected to experiment in the manner above described, the former will act the part of the more powerfully diamagnetic needle, and produce similar effects in the magnetic field.

We now pass on to the demonstration of the proposition, that it is not necessary that the crystallized masses should be elongated to produce the effects exhibited by the prisms in the experiments already recorded. Let us suppose the ends of our rectangular box to be composed of cubes, instead of elongated masses, of crystallized bismuth, and let the planes of principal cleavage be supposed to be parallel to the face $a\,b$, fig. 5. Let the continuous line $d\,e$ represent an indefinitely thin slice of the cube passing through its centre, and the dotted line $g\,f$ a similar slice in a perpendicular direction. These two slices manifestly represent the case of the cross in fig. 4, and were they alone active, the rectangular box, in a uniform field of magnetic force, must turn in the direction of the arrow. Comparing similar slices *in pairs* on each side of those two central slices, it is

Fig. 5.



manifest that every pair parallel to the line $d\,e$ represents a stronger mechanical couple than every corresponding pair parallel to $f\,g$. The consequence is, that a cube of crystallized bismuth suspended in the manner described, in a sufficiently uniform field of magnetic force, will move in the same direction as the cross in fig. 4: its centre of gravity will therefore *approach* the pole N, which was to be demonstrated.

This deduction is perfectly illustrated by experiment. It is manifest that the effect of the pole S upon the cube adjacent to it is to increase the moment of rotation of the rectangular box: the same reasoning applies to it as to the pole N.

Referring to fig. 27*a*, page 41, it will be seen that we have here dealt with the second and gravest objection of M. MATTEUCCI, and converted the facts upon which the objection is based into a proof of diamagnetic polarity, so cogent that it alone would seem to be sufficient to decide this important question. Holding the opinion entertained by M. MATTEUCCI regarding the nature of diamagnetic force*, his objection must have appeared to him to be absolutely unanswerable: I should be glad to believe that the remarks contained in this 'Appendix' furnish, in the estimation of the distinguished philosopher referred to, a satisfactory explanation of the difficulty which he has disclosed.

Let me, in conclusion, briefly direct the reader's attention to the body of evidence laid before him in the foregoing pages. It has been proved that matter is repelled by the pole of a magnet in virtue of an induced condition into which the matter is thrown by such a pole. It is shown that the condition evoked by one pole is not that which is evoked by a pole of an opposite quality—that each pole excites a condition peculiar to itself. A perfect antithesis has been shown to exist between the deportment of paramagnetic and diamagnetic bodies when acted on by a magnet alone, by an electric current alone, or by a magnet and an electric current combined. The perplexing phenomena resulting from molecular structure have been laid open, and the antithesis between paramagnetic and diamagnetic action traced throughout. It is further shown, that whatever title to polarity the deportment of a bar of soft iron, surrounded by an electric current, and acted on by other magnets, gives to this substance, a bar of bismuth possesses precisely the same title: the disposition of forces which, in the former case, produces attraction, produces in the latter case repulsion, while the repulsion of the iron finds its exact complement in the attraction of the bismuth. Finally, we have a case adduced by M. MATTEUCCI which suggests a crucial experiment to which all our previous reasoning has been submitted, by which its accuracy has been proved, and the insufficiency of the assumption, that the diamagnetic force is not polar, is reduced to demonstration. When we remember that against all this no single experimental fact or theoretic argument† which can in any

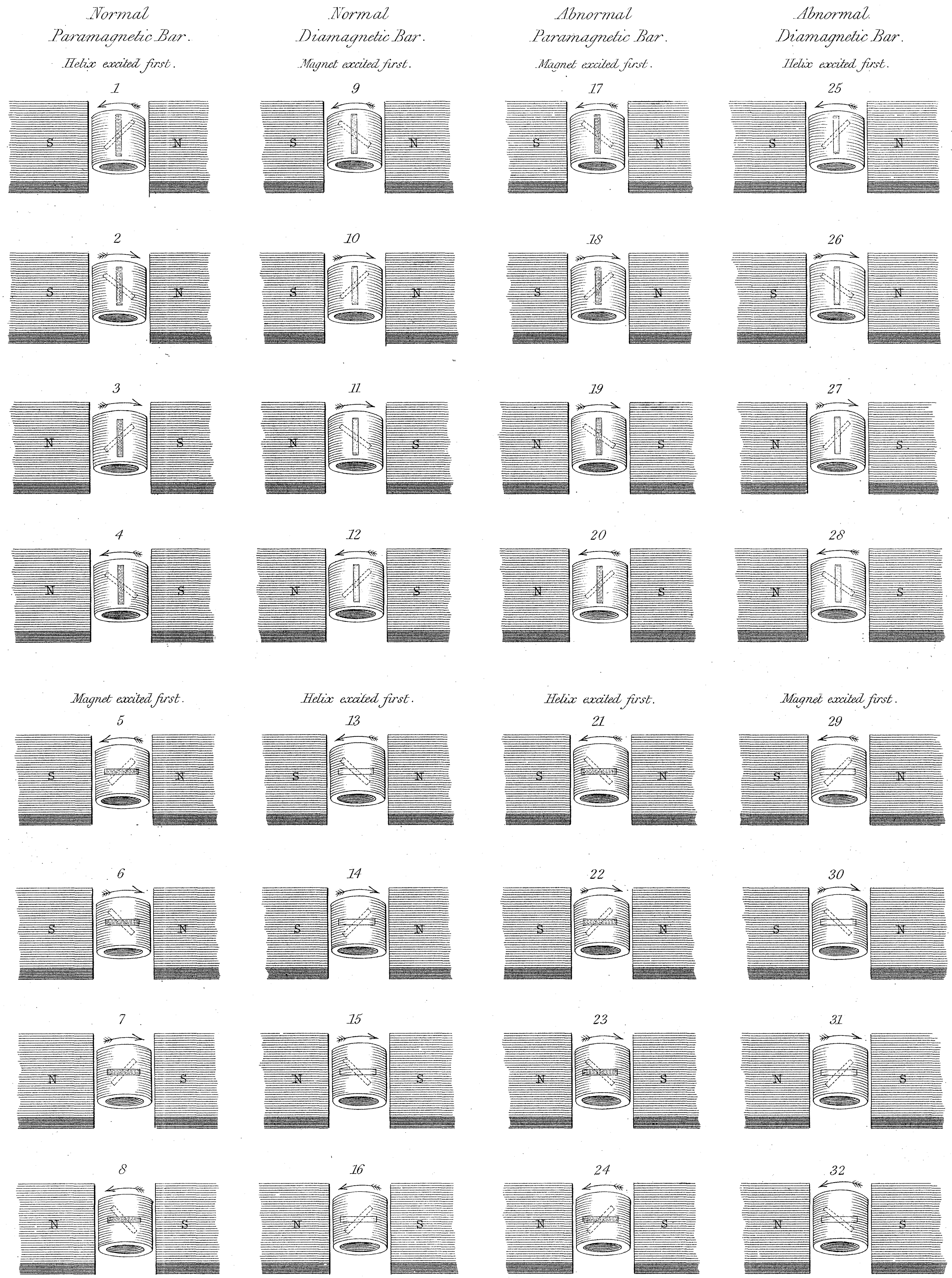
* Il ne peut exister dans les corps diamagnétiques une polarité telle qu'on la concoit dans le fer doux."—*Cours Spécial*, p. 201.

† I ought perhaps to except an argument of Professor W. THOMSON's, which professes to prove that an absolute creation of force, and the setting up of a perpetual motion, would follow, if diamagnetic polarity were

degree be considered conclusive has ever been brought forward, nor do I believe can be brought forward, the conclusion seems irresistible, that we have in the agency by which bodies are repelled from the poles of a magnet, a force of the same dual character as that by which bodies are attracted; that, in short, "diamagnetic bodies possess a polarity the same in kind but the opposite in direction to that possessed by magnetic ones."

conceded. While expressing my admiration of the ingenuity of Mr. THOMSON's reasoning, it appears to me to labour under the disadvantage of proving too much, his conclusion being equally fatal to polarity of all kinds. The argument, I believe, was first publicly urged against myself at the Belfast Meeting of the British Association; but at the Liverpool Meeting last year Professor THOMSON himself admitted "that he had not perfect confidence in the truth of the conclusion, as one of the assumptions on which the reasoning was founded admitted of doubt."—See Athenæum, 1854, p. 1204. Indeed, from many of his published papers, it might be inferred that Mr. THOMSON actually *assumed* what I, in the present memoir, have attempted to *prove*.

I refrain from alluding to the negative results obtained by Mr. FARADAY in repeating M. WEBER's experiments; for though admirably suited to the exhibition of certain effects of ordinary induction, Mr. FARADAY himself has shown how unsuitable the apparatus employed would be for the investigation of the question of diamagnetic polarity. See Experimental Researches (2653, 2654), vol. iii. p. 143.—J. T., May 9, 1855.


Normal Paramagnetic Bar.
Normal Diamagnetic Bar.
Abnormal Paramagnetic Bar.
Abnormal Diamagnetic Bar.
Helix excited first.
Magnet excited first.
Magnet excited first.
Helix excited first.
1
9
17
25
2
10
18
26
3
11
19
27
4
12
20
28
Magnet excited first.
Helix excited first.
Helix excited first.
Magnet excited first.
5
13
21
29
6
14
22
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J. Basire, sc.

Fig. 5.

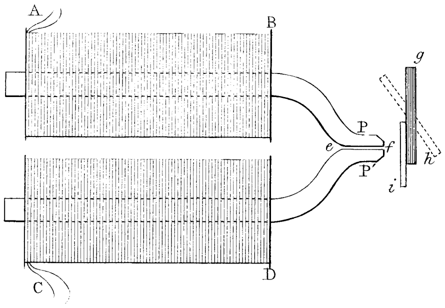
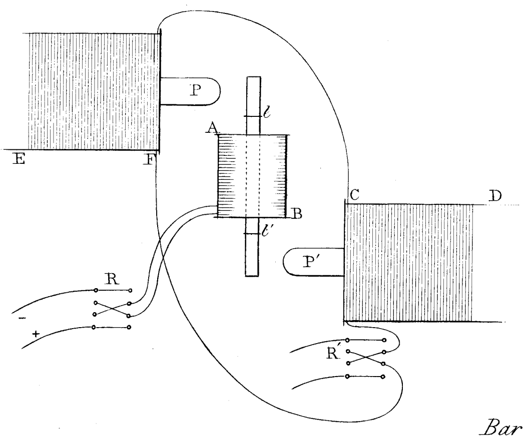
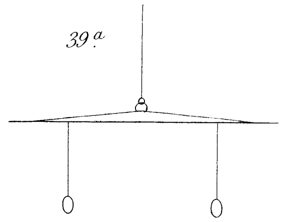


Fig. 39.



39.ª



Bar of Iron.

Bar of Bismuth.

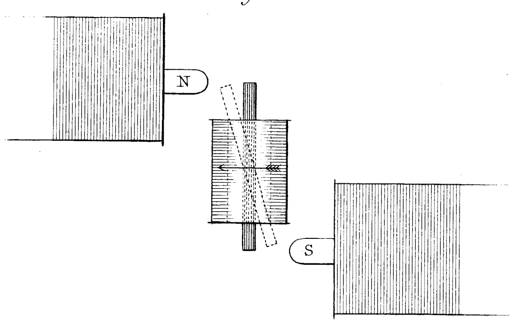
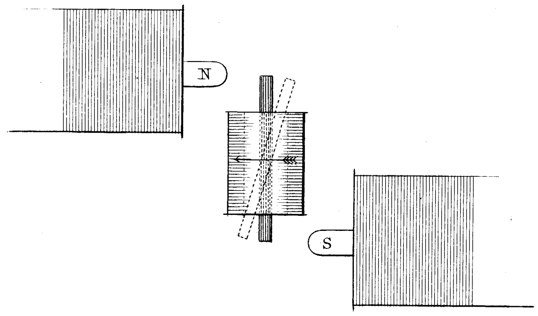


Fig. 40.



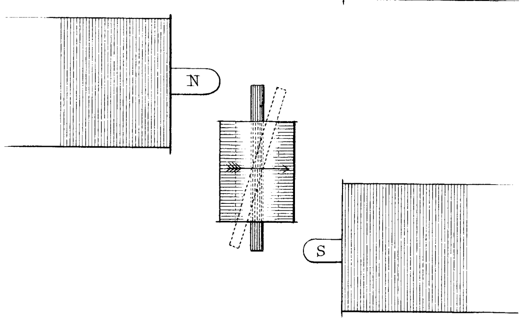
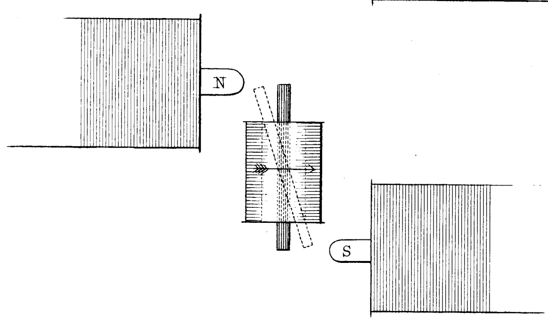


Fig. 41.



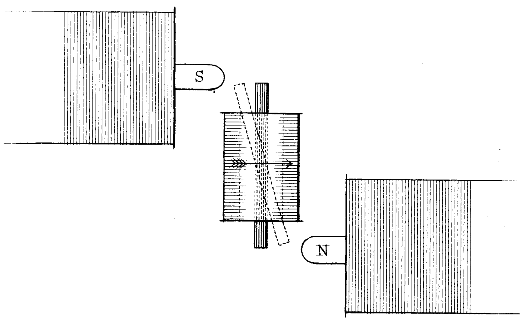
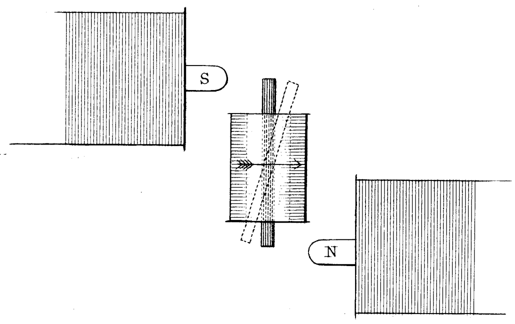


Fig. 42.



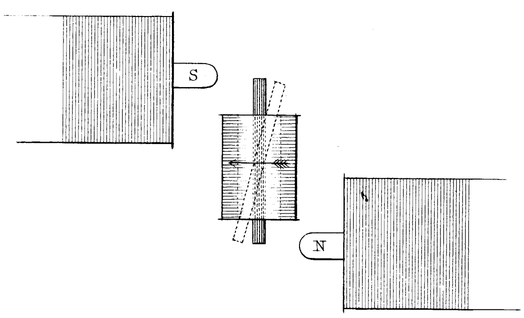
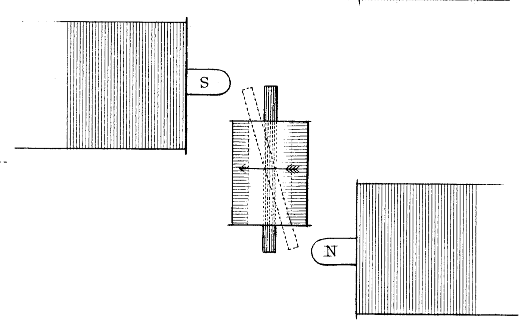


Fig. 43.



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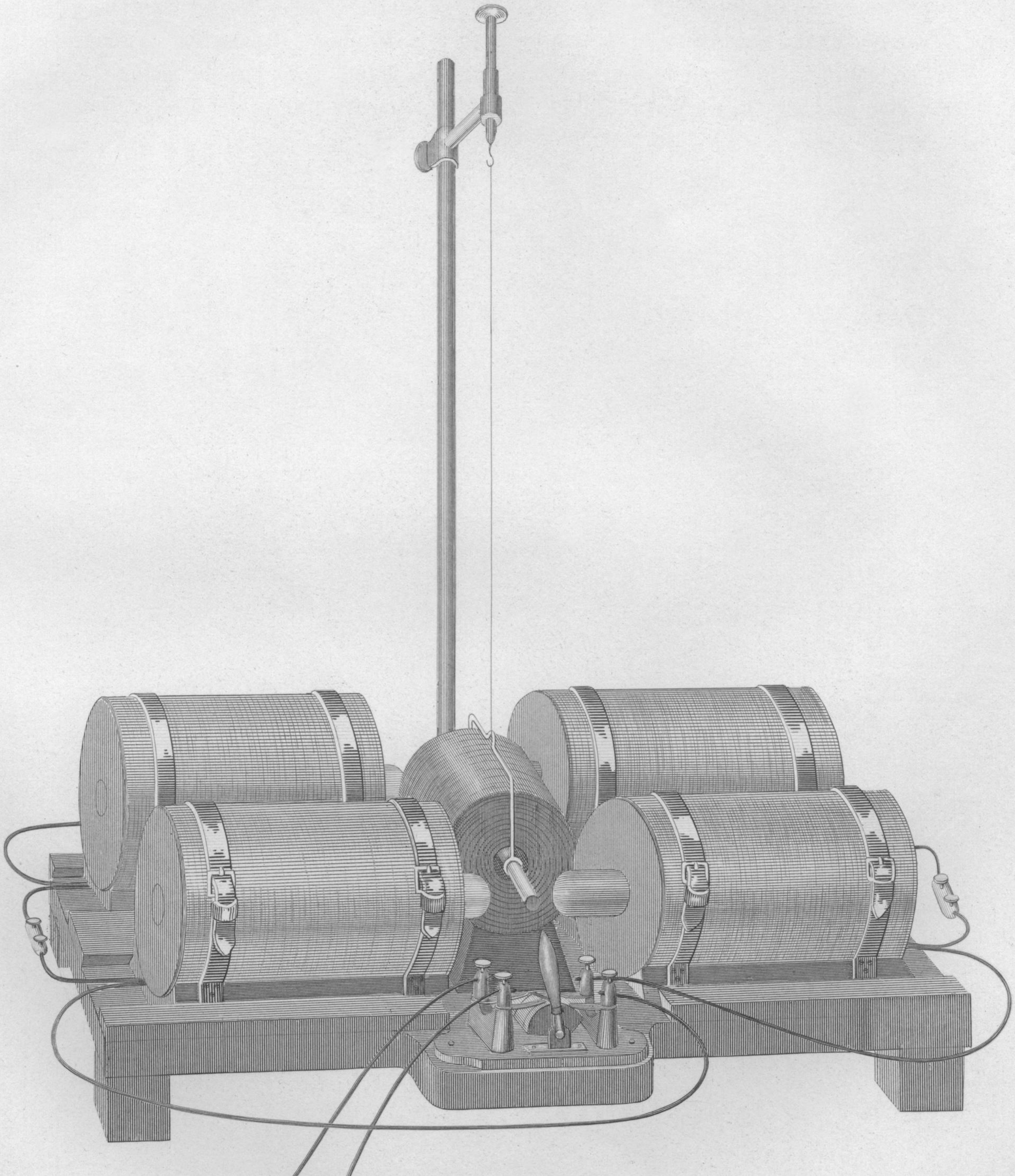

C. Becker, del. *J. Basire, sc.*